FREE FLIGHT COCKPIT DISPLAYS OF TRAFFIC AND WEATHER INFORMATION: EFFECTS OF DIMENSION AND DATA BASE INTEGRATION

BY

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FREE FLIGHT COCKPIT DISPLAYS
OF TRAFFIC AND WEATHER INFORMATION:
EFFECTS OF DIMENSION AND DATA BASE INTEGRATION

ABSTRACT

As the concept of Free Flight continues to be explored, it becomes increasingly evident that pilots must have displays that effectively depict traffic and weather information as more and more responsibility for separation from such hazards transfers from air traffic controllers to pilots. This research effort seeks to address two display design issues: dimensionality (3D perspective versus 2D coplanar displays) and database integration (separation or integration through overlays of traffic and weather information within displays). It was hypothesized that the 2D displays would result in fewer traffic and weather conflicts then the 3D displays, replicating the findings of Merwin and Wickens (1996) regarding traffic avoidance. As suggested by the Proximity Compatibility Principle (Wickens & Carswell, 1995), the data base integrated displays were expected to result in fewer conflicts than the separated displays for trials in which both weather and traffic were critical for maneuver choice. Finally, as revealed in Merwin and Wickens (1996), it was hypothesized that display type and scenario geometry would effect maneuver strategies.

17 general aviation flight instructors flew a series of trials with four display types in which dimensionality, database integration, and hazard geometries were manipulated. Analyses of the data revealed that the 2D displays result in a smaller percentage of conflicts with traffic and weather hazards. The results regarding database integration suggest that displays in which traffic and weather are overlaid result in fewer hazard conflicts for trials in which both hazard types are critical to maneuver selection. Display type and scenario geometry were also found to effect maneuver strategies, including a pronounced 2D advantage for trials in which the traffic is descending or ascending, while performance for level traffic trials is similar across display types.

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1. INTRODUCTION

The concept of Free Flight involves the transfer of responsibility for separation from hazards, such as weather and traffic, from air traffic controllers to the pilots (RTCA, 1995). It has been proposed that by allowing pilots to maneuver more freely, rather than adhering to strict, pre-approved flight plans, fuel consumption and delays could be decreased. The potential benefits of Free Flight depend on the ability to maintain, if not improve, current levels of safety.

Communication between pilots, both within and between aircraft, and with air traffic controllers is one of the factors critical to the success of Free Flight. The transfer of responsibility between pilots and air traffic controllers is a complex issue which has led to accidents and incidents in the past. For example, a Lear 24B flying from Palm Springs to Los Angeles at an altitude of 9,000 feet, crashed into a mountain where the minimum altitude was 13,000 feet. Why were the pilots flying at a lower altitude than required? The accident investigation report focused on the communication between the pilots and the controller. It was noted that the responsibility for separation from terrain had recently shifted from pilots to air traffic controllers due to new radar technology. Conclusions from the accident investigation suggest that the pilots assumed the controller was assuring safe separation from the terrain, however radar coverage in the area was not provided (National Transportation Safety Board, 1977). Breakdowns in communication regarding the responsibility for separation from traffic and weather could potentially lead to similar incidents if pilot-controller interactions are not considered during the implementation of Free Flight.

Empirical evidence suggests that lapses in communication, such as in the learjet accident just discussed, result in performance decrements. Foushee and Manos (1981) examined the effects of communication on performance in the cockpit by analyzing the cockpit voice recordings from Ruffell Smith's (1979) flight simulation study. Results revealed that performance decrements were found for crews in which there was less communication between pilots. In addition, the quality of the communication was a critical factor in performance. In their review of studies regarding aircraft accidents and incidents attributed to "pilot error," Helmreich and Foushee (1993) concluded that communication and coordination play a more pivotal role in the mishaps than do "stick and rudder" proficiency. Billings and Cheaney (1981) also reported evidence of the critical role of communication in aviation. They found that over 70% of the Aviation Safety Reporting System incident reports collected from 1976 to 1981 involved problems with the transfer of information. The breakdowns in communication were most often associated with pilots' interactions with controllers, rather than with other crew members.

Thus the implementation of Free Flight will depend upon the communications, distribution of authority, and shared information between pilots and ATC, and between pilots and pilots. While much information sharing may be done through voice channels, an opportunity is provided by display channels, visually portraying to each pilot what the other pilots are doing, and to ATC what all pilots in the area are doing. Such opportunities are provided by the existence of accurate Global Positioning System (GPS) based sensors on board aircraft, and mode S radar that can rapidly distribute information in and between all players (pilots and ATC). This thesis addresses the important issue of how such information should be displayed to the pilots.

The concept of Free Flight may require the integration of both weather and air traffic information in order to facilitate the pilot's understanding of the surrounding airspace. For

example, a pilot deciding on a maneuver to avoid traffic may have to consider the possibility of hazardous weather in the direction of the proposed maneuver. In 1991 it was estimated that weather played a role in 40% of aviation accidents and contributed to 50% of the delays for commercial flights (Hansen, 1991). Due to the tremendous impact of weather on safety and aircraft operations it is critical that information regarding weather be depicted accurately. Currently pilots have access to weather and traffic information; however, ATC is largely responsible for coordinating maneuvers to avoid such hazards. Under Free Flight conditions the pilots must rely more heavily on displays of traffic and weather information to detect and avoid hazards in the air. With the added responsibility for maintaining separation, it is critical that the displays be designed so as to minimize the workload associated with the transfer of authority from ATC to the flightdeck. The present research evaluates various ways of depicting both traffic and weather hazards. One issue to be examined is the dimensionality of the display format. Because the relative costs and benefits of two-dimensional (2D) and three-dimensional (3D) displays were addressed in a recent review by Merwin and Wickens (1996), the issue of dimensionality is not discussed in detail here. The focus of this literature review is on research relevant to the integration of weather and traffic information in aircraft displays.

In order to understand better the costs and benefits of integrating weather and traffic data bases, as opposed to presenting them separately, we can specify the four display types relevant to the present experiment (see Figure 1). These displays can vary according to dimensionality (2D or 3D) and data base integration (separated or integrated). The four display types are further broken down into panels based on their dimensionality and level of data base integration. The display format in the upper left corner, Display A, consists of four panels and is the least integrated of the displays. Weather and traffic information are displayed in separate panels and are further divided

into top down and forward view panels, based on the 2D or coplanar format. It is important to note that the 2D displays in this experiment are coplanar displays, as opposed to single panel 2D displays which depict only one view (i.e. forward or top down). Display A has the largest number of panels, which results in high scanning requirements to integrate information between panels. The four panel display benefits from decreased effects of clutter within each panel. In addition, the use of a 2D view better supports precise estimates of specific data points along vertical and lateral axes than do the 3D perspective displays that may suffer from line-of-sight ambiguity due to the representation of three axes on a 2D display screen (Merwin & Wickens, 1996; Wickens, 1996). The opposite extreme is represented in the lower right corner of Figure 1 in Display D. The single panel 3D display combines information from both the vertical and lateral axes, and does not require the pilot to scan between panels to integrate weather and traffic information. Display D does, however, suffer from increased clutter, especially when hazards from both data bases are present. The displays in the upper right and lower left corners of Figure 1 consist of two panels each. Displays B and C are expected to have moderate levels of interference from visual scanning between panels and clutter within panels. While Display B may suffer from line-of-sight ambiguity due to the 3D perspective format, search times may be increased in Display C as a result of the added clutter from the overlapping data bases.

The literature regarding which display format might be superior for the task of processing weather and traffic information is relevant to the extent that it addresses one or more of three critical information processing mechanisms: scanning, cognitive integration and focused attention. These three mechanisms are applied as users attempt to integrate two spatial domains of information. **Scanning** between spatially separated panels will always take additional time and hence will be a process whose influence will favor the single panel over the two panel, and the

two panel over the four panel configurations. Furthermore, the cost of scanning will be mediated by the demands for **cognitive integration** between data bases represented in the two panel display (Haskell & Wickens, 1993; Vincow & Wickens, 1993; Wickens & Carswell, 1995; Wickens, Merwin, & Lin, 1994). If, for example, the pilot must decide on a maneuver to avoid traffic, but some of the plausible traffic avoidance maneuvers might direct the pilot into weather (i.e., both weather and traffic information must be considered to implement a safe maneuver), then it should be helpful to have both domains represented in a single coordinate space (data base integration). If the weather and traffic information is not integrated on the display, then the image of the spatial configuration in one space must be retained in working memory as the gaze is transferred to the other space, a cognitive operation that is vulnerable to interference (Liu & Wickens, 1992). As noted in Merwin & Wickens (1996), a corresponding argument can be made regarding integration of lateral and vertical axes. For example, if a lateral traffic avoidance maneuver may bring the aircraft into conflict with a climbing or descending plane, it would be useful to have both axes represented in the same display space. With the axes displayed together in an integrated format, the vertical and lateral separations relevant to a single decision could thus be considered simultaneously.

On the other hand, with regard to both dimensionality (left versus right displays of Figure 1), and data base integration (top versus bottom displays of Figure 1), if a task does not require that judgments of one 2D plane (or one data base) be dependent on consideration of the other, then cognitive integration becomes unnecessary. That is, all the information can be extracted from a single fixation on one plane or data base. Generically we refer to these as **focused attention** tasks (i.e., focused attention on one data base, one axis, or both). Review of the literature on such focused attention tasks (Wickens & Carswell, 1995) reveals the negative impact of clutter on this

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third mechanism of focused attention. The disruptive effects of clutter will be increased when more spatial information is combined in a given region (through the use of a 3D configuration) and will be particularly harmful to the extent that imagery is overlapping (through data base integration).

Overall, predicting the tradeoff between these factors is difficult. The literature on dimensionality was reviewed by Merwin and Wickens (1996). It was noted there that the advantages of dimensional integration (use of 3D instead of 2D) often emerge when problems require joint consideration of lateral and vertical axes (e.g., Wickens, Merwin, & Lin, 1994), but are reduced and sometimes reversed when such task integration is not required. Under the latter circumstances the problems of line-of-sight ambiguity dominate as a cost for the 3D displays.

Merwin and Wickens (1996) conducted an experiment to assess the effects of display dimension on conflict detection and avoidance. 30 flight instructors flew a series of trials on a desktop flight simulator with either a 3D perspective display or a 2D coplanar display. During the first session, subjects were instructed to detect and avoid conflicts with one other aircraft. A second intruder aircraft was added for trials during the second session. The results of Merwin and Wickens' (1996) experiment revealed that overall the 2D coplanar display better supported traffic avoidance than the 3D perspective displays (differentiated by elevation angles of 30 and 60 degrees). In addition, traffic avoidance was found to vary by the vertical behavior of the traffic. When the traffic was level, performance on the three displays was similar, but differences in hazard avoidance emerged when the traffic was non-level (ascending or descending). Thus, the 3D ambiguity costs were greatest for trials in which the traffic's behavior was unconstrained (non-level), relative to the level traffic trials. Costs associated with 3D ambiguity and the estimation of points or trajectories within a 3D space were also revealed in studies of Air Traffic Control (ATC)

by May, Campbell, and Wickens (1996), and Wickens, Miller, and Tham (1996), and Boyer, Campbell, May, Merwin, and Wickens' (1995) study of weather and terrain awareness.

In contrast to the extensive data reviewed by Merwin and Wickens (1996) on dimensional integration, far less empirical data appears to exist on the performance effects of data base integration. While there is indeed a large data base of studies on integrated displays (see Bennett & Flach, 1992; and Wickens & Carswell, 1995 for review and summary of much of this work), it is less relevant to the current issues because most of these studies focus on the integration of non-metric or non-map data bases. That is, the **relative spatial position** of entities within the to-be integrated data bases is not important, and so the designer is able to **configure** these entities in ways that best serve the user's tasks. The most important conclusion that such work reveals that is relevant for the current discussion, is that rendering items close together in physical space generally facilitates their cognitive integration, as long as such close physical proximity does not also disrupt the operator's ability to focus attention on entities as needed.

In contrast, for the integration of map or metric data bases, the meaning of the entities is explicitly linked to positions on some coordinate axes, and cannot be moved. For instance, the location of a terrain feature or aircraft relative to the coordinate system in geographical space cannot be moved in order to facilitate their integration. Correspondingly, the location of entities of other "maps", such as those of weather or anatomical features of the body can not be altered as different layers are overlaid (e.g., muscular system, skeletal system, nervous system, location of pathologies, etc.), because the existing spatial relations of these entities are critical.

These constraints define four important perceptual/cognitive factors relevant to the integration or separation of data bases:

1. When data bases are physically separate, there are scanning costs as the eye must move back and forth between the relevant spaces.

2. When the data bases are separate, and integration of the data must be performed between the two data bases, then the spatial image of entities within one data base must be maintained in working memory as the other data base is examined, a process that is more error-prone than if the coordinate systems of the two data bases are physically aligned (through overlap).

3. When the data bases are overlapping, then the resulting clutter of close spatial proximity may either mask critical features making them difficult to find (visual search), or obscure their contours, and thereby make them difficult to interpret, even after they are located.

4. When the data bases are overlapping in a common coordinate space, then the added visual markings in close proximity may increase the confusability of those entities, making it more difficult to automatically keep track of which markings belong to which data base.

Relevant to our review are studies that bear on the relative costs of these four different metrics; how display design parameters can moderate these costs, and, in particular, comparative studies that have evaluated separated versus integrated data bases, to assess how the costs tradeoff against each other.

2. EMPIRICAL LITERATURE

2.1 Scanning Costs

The literature on visual scanning is extensive, although much of it is at best peripherally relevant. Such literature suggests that scanning between two spatially separated reference frames takes time; but the time cost is not a linear function of the degree of separation. Rather, a major penalty is added whenever any scan is triggered, and only smaller penalties are added as the extent of scanning is increased (Martin-Emerson & Wickens, 1992).

2.2 Integration Costs

A fundamental premise of the Proximity Compatibility Principle (Wickens & Carswell, 1995), is that visual scanning interferes with the working memory demands of retaining information from one display location, that must be used for comparison at a different location (Faye, 1995; Liu & Wickens, 1992; Vincow & Wickens, 1993). Other research suggests that the quality or resolution of spatial information degrades over time (Logie, 1995; Moray, 1986) in such a way as to predict that the accuracy of locating an entity in the spatial framework of one data base will be degraded by the time that the eye has fixated upon, and oriented to a second data base.

2.3 Masking and Clutter Costs

There is by now a well documented body of literature pertaining to the difficulties encountered in extracting visual information when other information lies within close spatial proximity (Carter & Cahill, 1979; Eaton, 1993; Eriksen & Eriksen, 1974; Hofer, Palen, & Possolo, 1993; Houck, Kelly, & Wiedermann, 1986; Jackson, Johnson, Maloney, Millar, & Kersteen, 1982). In the domain of map use, many of these conclusions derive from studies that demonstrate the value of decluttering schemes (Hofer et al., 1993; Martens & Wickens, 1995; Mykityshyn, Kuchar, & Hansman, 1994; Schultz, 1986).

2.4 Data Base Confusion

A second source of difficulty, similar, yet distinct to the issue of clutter is the mental confusion that can arise when several sources of information share common physical features (i.e., in this case overlapping space). Work by Hess and Detweiler (1995), for example, documents the role of spatial separation in assisting a "keeping track" task. When data bases overlap, and spatial separation is thereby prevented, other techniques are available to aid the operator in maintaining a discrimination, such as color coding (Christ, 1975; Hess & Detweiler, 1995; Hoffman, Detweiler, Conway, & Lipton, 1993; Jones, 1962; MacEachren, 1994; Wickens & Andre, 1990); or intensity coding (Brown, 1991; Pickett, Levkowitz, & Seltzer, 1990; Schultz, 1986; Martens & Wickens, 1995).

2.5 Map Studies

There are a large number of studies in the cartography and visualization literature that propose algorithms and techniques for overlaying various data bases (Brown, 1993; Eaton, 1993; MacEachren, 1994). Johnston, Singer, and Thorpe (1978) addressed the limited ability of individuals to integrate information from numerous overlaid plastic maps for land use management projects. The authors recognized the potential benefits from the use of computer map overlays to integrate such data bases as population density, soil samples, city and county boundaries, and precipitation. Other studies discussed the importance of integration in future aviation displays (Bauhof, 1993; Grossman, 1983; Houck, Kelly, & Wiedermann, 1986; Jesuroga, 1993; Prince, 1980). For example, Williams and Mitchell (1993) described a prototype cockpit display to overlay flight path information onto a terrain map. Heppner (1993) also described an aviation display which integrates information through data overlays. The proposed display allows dispatchers to view weather, route information, and aircraft location data overlaid on a geographical map (see Figure 2). Research regarding techniques for overlaying data bases is particularly relevant to the single panel display (Display D) in Figure 1, in

which the weather and traffic data bases are integrated within the same 3D coordinate space. Unfortunately, most of this work is not empirically based, and does not assess human performance when different techniques (i.e., color coding, intensity coding) are compared, nor when overlaid data bases are compared with spatially separated ones.

However, certain conclusions do emerge from the smaller subset of studies that examine empirically human performance issues relevant to the issue of overlaid data bases. For example, Schultz (1986) examined a task in which operators were requested to locate targets in one domain on a cluttered map. Schultz found performance was best when the map was entirely decluttered of all other domains, and when much of the nonessential symbology was "simplified," so that it looked substantially different from the target symbology. Performance in a "lowlighted" condition, in which nontarget information was represented at reduced intensity was not as good, but was still better than performance in the full clutter condition.

Jackson, Johnson, Maloney, Millar, and Kersteen (1982) addressed the issue of clutter in their discussion of on-board displays to integrate and/or overlay communication, navigation, weather, and ship system information. The authors suggested allowing the user to de-clutter displays by removing unnecessary data from the screen. One of the costs of this approach to de-cluttering is the lack of ability to integrate information across data types. If, for example, the user needs both weather and navigation information simultaneously the user is required to switch back and forth between the two data types, resulting in higher workload and increased access times.

2.6 Tradeoff Investigations

In spite of the large literature addressing human factors of map design, there appear to be very few studies that have examined one or both of two kinds of tradeoffs that underlie the research program we undertake here: (1) the tradeoff between visual scanning and cognitive integration costs

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with separate displays, versus confusion and clutter with integrated displays, and (2) the tradeoff of task types; between tasks that require focusing of attention on one domain or the other, favored by separate domains, and tasks that require integration of information, more favored by overlapping domains.

Considerable insight as to the nature of the first tradeoff may be gained from studies of head-up displays (HUDs), in which imagery related to flight control is presented in either a HUD configuration, in which case the imagery data overlays the background view of the world, or in a head-down location, in which case the two images are physically separated (Weintraub, Haines, & Randle, 1985; Wickens & Long, 1995; Martin-Emerson & Wickens, 1992; Wickens, Martin-Emerson, & Larish, 1993; Lasswell & Wickens, 1995; May & Wickens, 1995. See Wickens, 1995 for a summary). The general consensus of this research is that for most information for which the focus of attention is required, the advantages of reduced scanning fostered by overlapping (HUD) imagery, slightly outweigh the costs of clutter; hence favoring a solution of data base overlap. These advantages tend to be enhanced when there is a spatial relatedness between the imagery in the two domains (i.e., an information integration task); but reduced and sometimes reversed when there is no spatial relatedness. When there is no task relatedness (i.e., the task calls for focused attention on one domain data base -- near or far -- to the exclusion of the other), and in particular, when task related events occur very infrequently (e.g., an unexpected target), the costs of clutter in the HUD tend to predominate.

Regarding the tradeoff between focused attention and integration (divided attention) tasks between overlapping data bases, few studies of map interpretation examine the contrast. Martens and Wickens (1995) proposed the use of a lowlighting technique as a solution to the problem of clutter, rather than removing data as in the previous study. A display was designed which represented two domains, a road map with nine labeled destinations (fixed domain) and nine

moving vehicles (varied domain). Rather than erasing information to declutter the display, Martens and Wickens hypothesized that varying the intensity between the two display domains would support both focused and divided attention tasks. Overall results revealed that response times for both integration and focused attention tasks decreased as the difference in intensity increased. Thus, the results of the Martens and Wickens study suggest that with proper attention to intensity coding techniques, tradeoffs between focused attention and integration tasks are not inevitable.

Our review above focused primarily upon issues of data base integration, and naturally addressed some of the techniques (lowlighting, color coding) that can assist the operator with parsing the information space and focusing attention, when all information is in close spatial proximity. In this section, we provide a brief overview of some techniques that have been employed to facilitate performance in conditions in which data bases are separate, but information must be integrated between and across them. In particular we consider here the technique of **visual momentum** (VM). VM was originally used by screen editors as a technique to give viewers a sense of continuity across different scenes (Hochberg & Brooks, 1978). Subsequently Woods (1984) considered applications of visual momentum techniques to display design, and proposed a series of techniques by which this might be accomplished (see also Wise & Debons, 1987).

A recent program of investigations focused attention on the VM technique of **anchoring**, whereby techniques are used to show how the spatial position and orientation of items in one spatial map, are represented or "anchored" in a different map. Some of this work was spawned by the demonstration by Aretz (1991) of the utility of a "wedge" (see Figure 3) to represent how the forward field of view observed by a pilot is reflected on a top down map of the region through which the pilot travels (Faye, 1995; Olmos, Liang, & Wickens, 1995). Neale (1995) demonstrated the performance

benefits of providing an overview map and salient landmarks as VM techniques. Andre, Wickens, Moorman, & Boschelli (1991) successfully evaluated the anchoring technique of color coding, to show how the four cardinal directions (each colored differently) can be represented in both a forward view and a top down rotating map in a simulated aircraft navigation task.

Another visual momentum technique is to employ unique visual coding (e.g., color, flashing, highlighting) to identify (and thereby link together) the same entity that is represented in different spatial frameworks. A great deal of research for example demonstrates that flashing or uniquely colored symbols are effective techniques for focusing the user's attention on the colored or flashed entity (Carter & Cahill, 1979; Goldstein & Lamb, 1967; Smith & Goodwin, 1971). On the other hand, fewer studies examine the extent to which flashing (or color coding) the same entity within two non overlapping spatial frameworks, can assist the operator with integrating spatial information between the two data bases (i.e., as in plotting a maneuver that must avoid both traffic (data base 1) and weather (data base 2). A partially relevant study was conducted by Shontz, Trumm, and Williams (1971), who evaluated the impact of color coding on search time using aeronautical charts. Subjects were presented with and studied sketches consisting of significant terrain features and checkpoint information. The subjects then viewed an aeronautical chart with either color-coded or un-coded checkpoints and reported the quadrant of the desired checkpoint once it was located. The task simulated a pilot seeking orientation by comparing information observed from the cockpit (sketch = data base 1) to a map (aeronautical chart = data base 2). Search times were significantly faster when color-coded maps were used, supporting the use of color to link information between displays.

In summary, support for the use of 2D coplanar displays over 3D perspective displays for hazard avoidance is found in Merwin and Wickens (1996). The literature discussed also tend to

support the use of integrated displays when data must be combined across different domains. Augmentations such as lowlighting for integrated displays and visual momentum techniques, including highlighting, color and blink coding, for separated displays were discussed as methods to compensate for drawbacks associated with each display type. However there is a lack of empirical studies on the spatial integration of information from different spatially defined data sets. Thus, the final results of the present experiment will be critical to determining the effectiveness of overlaid data bases in Free Flight displays and a variety of other applications.

The current experiment also provides examinations of the stereotypical responses pilots make when confronting a future loss of separation, when not under positive control by ATC. Merwin and Wickens (1996) found that the pilots tend to make more vertical than lateral maneuvers while avoiding traffic hazards. Regarding dimensionality, the authors found that the 2D display format fostered more combined maneuvers, as opposed to the more strictly vertical maneuvers made with the 3D displays. Maneuver strategies also varied according to the vertical behavior of the other aircraft. For instance, differences in performance with 2D and 3D displays were most pronounced when traffic was non-level (ascending or descending).

The simulated en route flying task, in the current effort, required the pilots to fly to a waypoint while avoiding weather and traffic hazards. Pilots were instructed to make maneuvers as efficient as possible, keeping flight path deviations at a minimum so as to reach the waypoint in the least amount of time while avoiding conflicts with hazards along the way. Performance measures, including time to decide upon a maneuver, time to complete a trial, percentage of trials with traffic and weather conflicts, lateral and vertical deviations from the initial flight path, as well as preference ratings are used to explore the issues of dimensionality and data base integration (as depicted in Figure 1). It was hypothesized that Displays A (2D separated) and C (2D integrated)

would result in the best performance, regarding the measures listed previously, as compared to the 3D displays due to the 2D advantage revealed in the literature (Merwin & Wickens, 1996). By extending the Proximity Compatibility Principle (Wickens & Carswell, 1995) to the use of overlays, it was expected that the data base integrated displays (C and D) would be relatively more advantageous than the separated displays (A and B), particularly for scenarios in which consideration of both weather and traffic was critical for efficient maneuvering and hazard avoidance.

3. METHOD

3.1 Participants

All of the participants were licensed flight instructors from the University of Illinois Institute of Aviation and received eight dollars per hour for their participation. There was a total of 17 participants, 10 males, and 7 females. 8 of the pilots had previously volunteered as participants in Merwin and Wickens' (1996) study. Participants ages ranged from 21 to 59, with a mean age of 31.9 years. The mean number of total flight hours was 3,944, and for IFR flight (both simulated and actual) the average number of hours was 385.

3.2 Displays

The four display types from Figure 1 will now be described in detail, with numbers annotated on the figures to indicate particular features of the four displays. Display A was a 2D coplanar display and consisted of four panels (see Figure 4). Traffic information was represented in the left 2 panels and weather information in the right 2 panels. Pilots were instructed that the weather hazards were to be considered as no-fly zones, in order to avoid maneuver biases that may exist regarding different types of weather conditions. It is assumed that the weather hazards could be generalized to other types of hazards such as special use airspace. The top 2 panels consisted of a top-down view, while the bottom 2 panels portrayed a forward view. Unique to the 2D displays (Displays A and C) were the solid yellow horizontal lines in the bottom panels (see Figure 4, #1) which represented the **current** vertical protected zone boundaries around ownship (1500 feet above and below ownship). Dashed yellow horizontal lines represented **predicted** vertical protected zone boundaries. Note: dashed lines are not present in Figure 4 because ownship is maintaining a constant altitude. In this figure the other aircraft is flying level within the vertical protected zone, at the same altitude as ownship.

There were many features common to the four displays. Along the right side of the screen there was always an Attitude Direction Indicator (ADI) and altimeter. The red "Restricted Flight" text appeared at the beginning of each trial and remained until the participant decided on a maneuver and pressed the trigger on the joystick. Heading information was provided at the top of the screen, overlaying the grid on the black background. Grid dots were separated by one mile, with one grid block being five miles long by five miles wide. The grid was always 5000 feet below ownship's current position, although this feature was not visible in the 2D displays.

Ownship (see Figure 4, #2) was always magenta and headed toward the top of the screen, beginning each trial at an altitude of 10,000 feet. Other aircraft (see Figure 4, #3) were gray under non-conflict conditions. Predictor lines (see Figure 4, #4) extended from the nose of each aircraft (matching the color of the corresponding aircraft) and represented the predicted flight path 45 seconds (4 miles) into the future. Orange threat vectors (see Figure 4, #5) extended from ownship's predictor line and pointed in the direction at which the other aircraft would pass closest to ownship if the pilot maintained the current heading and vertical velocity (see the top left panel of Figure 4). Threat vectors moved closer to ownship's nose as time to conflict decreased. The endpoint of the threat vector moved closer to the other aircraft's predictor line as the predicted separation decreased. When that separation was reduced to zero, it signaled that a loss of separation (penetration of the protected zone of 1500 feet above and below ownship and within a 3 mile radius of ownship) would occur at the point of closest passage, unless a maneuver was initiated to avoid it. Therefore, participants needed to avoid contact between the threat vector's endpoint and the other aircraft's predictor line. Weather hazards were depicted as red rectangles (see the right two panels of Figure 4, #6). The blue and yellow waypoint (see Figure 4, #7) was

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always at an altitude of 10,000 feet, directly in front of ownship at the beginning of each trial. Its horizontal position was depicted on the grid.

Display B was a 3D, separated traffic and weather display (see Figure 5). Traffic information was still presented on the left side of the screen with weather depicted on the right, as in Display A, but in a 3D (rather than 2D) format. All features of Display B were equivalent to those discussed for Display A. However, the solid and dashed yellow horizontal lines which were depicted in the forward view panel of the 2D displays were not present in the 3D displays.

There were also some features unique to the two 3D displays (Displays B and D). Green and yellow vertical posts extended from both ends of the predictor lines to the grid (see Figure 5, #8). The current and predicted horizontal position of ownship and other traffic could be determined by looking at the point at which the posts intersected the grid. The yellow zones on the posts (the black portions of the posts above and below the aircraft in Figure 5) represented the current and predicted vertical protected zone, 1500 feet above and below ownship. The yellow zones on the posts could be used to determine if the traffic was within (or would be within) the vertical boundaries of the protected zone. For instance, by comparing the current and predicted posts on the other aircraft in the picture, the subject could see that the traffic was currently below the yellow zone, but if they maintained their current flight path, the other aircraft would be in the middle of the vertical protected zone within 45 seconds. By comparing the lengths of ownship's posts to the other aircraft's the subjects could also obtain relative height information between the aircraft.

Also unique to the 3D displays was the weather hazard shadow: A blue "shadow" is projected onto the grid, representing the horizontal position and area of the weather (see Figure 5, #9). If the endpoints of ownship's green vertical posts intersected the grid within the "shadow",

ownship was either above, below, or within the weather. If a subject flew into a weather hazard, a weather conflict occurred: In all four displays, the wings of ownship turned red, and the center portion of the aircraft flashed yellow and red, during a weather conflict.

Display C was a 2D, integrated traffic and weather display (see Figure 6). Unlike Displays A and B previously discussed, in this 2D display the traffic and weather information was integrated or overlaid within the same panels. As with the other 2D display, the top panel portrayed a top-down view, while the bottom panel represented a forward view. Hence the symbology was the same as that described for Display A.

As noted by the zero separation of the threat vector from the intruder aircraft's predictor line, a predicted traffic conflict is portrayed in Figure 6: When a traffic conflict was predicted within the next 45 seconds, the other aircraft and its predictor line (from the end of the threat vector to the nose of the aircraft) turned white. The color coding of predicted traffic conflicts was consistent across all display types.

The dashed yellow horizontal lines mentioned in the discussion of Display A can be seen in the bottom panel of Figure 6 (#10). These lines represented the top and bottom of ownship's protected zone 45 seconds into the future. In Figure 6, the other aircraft is currently within the vertical boundaries of the protected zone because it is within the **solid** yellow lines. However, the end of the traffic's predictor line is outside the **dashed** yellow lines, indicating that if the subject continued along their flight path the other aircraft would be above the vertical protected zone within 45 seconds and ownship would no longer be in a conflict situation.

Display D was the 3D, integrated traffic and weather display (see Figure 7). This display integrated the traffic and weather information in a single panel. Both 3D displays (Displays B and D) were augmented with weather markers on ownship's post. If ownship was within 1500 feet

vertically of the bottom of the weather, a purple mark appeared on ownship's vertical post within the yellow zone. The marker's position corresponded with the altitude of the bottom of the weather. A red marker appeared if ownship was within 1500 feet from the top of the weather, and represented the altitude of the top of the weather. A purple marker appears on the vertical post above ownship in Figure 7 (#11), indicating that the subject was flying under the weather. An actual traffic conflict is also represented in Figure 7. When the other aircraft was currently within ownship's protected zone, the threat vector reached the nose of ownship, as noted previously, and the other aircraft turned yellow. It is important to remember that all conflicts (weather, predicted traffic, and actual traffic) could occur with all four displays. The symbology for the three conflict types remained consistent across displays.

3.3 Task

The participants were asked to fly a series of short trials (approximately 2 minutes per trial) with each of the four experimental displays on a Silicon Graphics personal IRIS system, with a joystick for maneuvering ownship. In each trial there was one other aircraft and one weather hazard. The participants were instructed to fly, as close as possible, to a prescribed heading and an altitude of 10,000 feet to a navigational waypoint while monitoring the display for potential conflicts with traffic and weather. If the weather was initially positioned in front of ownship, a conflict with the weather would occur if the pilot did not maneuver. If, on the other hand, the weather was initially to the left, right, above, or below ownship, the geometry of each trial was configured so that the pilot would have to maneuver to avoid a traffic conflict. When deciding on a maneuver, the pilots were required to consider the initial conflict as well as potential conflicts that could arise as a result of the alternative maneuvers that were considered. After assessing the situation and deciding on a maneuver, the pilots pressed the trigger on the joystick allowing them

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to maneuver freely. It was stressed that avoidance of traffic and weather were equally important, and that the primary goal of the pilot's task was to reach the waypoint as efficiently and rapidly as possible while maintaining safe separation from traffic and weather.

3.4 Experimental Design

A 2 x 2 factorial, within-subjects design was used. The factors of interest were dimensionality (2D and 3D) and data base integration (integrated and separated traffic and weather information). There was a total of 84 experimental trials, divided into four groups of 21. The order in which the display types and trial sets were presented were counterbalanced. Participants completed 21 trials with each display type.

Trials were assigned to the four groups in order to insure a variety of traffic patterns and weather locations were represented in each set of 21 trials. The other aircraft flew towards ownship at right and left 45, 90, and 135 degree angles. Whether the other aircraft was ascending or descending, leveling off above or below ownship, and passing in front of or behind ownship, was also varied. Weather hazards varied in their location either above, below, left, right, or in front of ownship. In the 3D displays, the elevation angle was 30° (as recommended by Merwin and Wickens (1996)), and there was an azimuth offset of 5° to the right to ensure that ownship's predictor line and posts would be visible when the pilot was flying straight (not turning right or left).

Trials also varied according to whether the pilots would tend to be biased toward or away from the other hazard when avoiding the initial conflict with weather or traffic. An example of a bias-toward trial is when the optimal maneuver to avoid a traffic conflict is to ascend, but a weather hazard is directly above ownship, preventing an ascent. If the weather is instead below ownship in the same scenario, a bias-away trial will result. There were also bias-toward trials in

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which the optimal maneuver to avoid the weather would result in a flight path toward the other aircraft. The order in which the different conflict geometry trials appeared within the four trial sets was determined by a pseudo-randomization procedure, to ensure that the bias-toward and bias-away trials were dispersed throughout the trial sets.

3.5 Procedure

The subjects were asked to participate for two hours a day for two days. On the first day the participants completed a pre-experiment questionnaire that included the following information: total flight hours, total instrument hours, age, gender, if they participated in the earlier Free Flight experiment (Merwin & Wickens, 1996), and if so, which display they viewed in that experiment (2D or 3D). Next, the participants were given instructions to read that were accompanied by pictures of the four display types, to familiarize them with the different displays and the symbology (see Appendix). Once the subjects understood the instructions, they flew eight introductory trials, two with each display type. The subjects then flew two practice trials, and 21 experimental trials on the same display. After a short break they flew another set of two practice and 21 experimental trials with one of the alternative displays.

On the second day, the subjects flew two sets of practice and experimental trials, separated by a short break. Upon completion of the last set of experimental trials, the subjects viewed four trials, one with each of the four displays. They were then presented with a post-experiment questionnaire and asked to rate the displays based on their preferences. They were also asked to provide information as to which characteristics influenced them on their ratings for the most and least preferred display. In addition, they were asked to provide information regarding what changes they would make to improve their most preferred display. Finally, the participants were asked for any other comments and were thanked for their time and cooperation.

4. RESULTS

The results of the study indicate differences between both 2D and 3D displays as well as between those which are integrated and separated. The differences involve a variety of issues such as the tradeoff between efficiency (reaching the waypoint as quickly as possible) and safety (avoiding traffic and weather hazards). Differences were also found regarding the strategies the subjects followed, reflected in biases to maneuver vertically and/or horizontally depending on the scenario and the display. Two-way Analyses of Variance were used to determine if differences between the displays existed and to contrast 2D versus 3D and integrated versus separated displays. Error bars represent two standard errors above and below the given value in the following graphs.

4.1 Trigger and Completion Times

Before maneuvering in each trial, subjects were asked to assess the situation and then press the trigger on the joystick to allow them to maneuver freely. The time at which the trigger was pressed represents the amount of time it took the subjects to decide on a maneuver. The shorter the trigger response time, the better the display is at portraying the necessary information to aid in decision making. Results for trigger response times did not reveal significant differences between the four displays, $F(3,48)=.97(NS)$ (see Figure 8).

Trial completion time was analyzed to evaluate the efficiency of the subjects' maneuvers. Lower trial completion times indicate more efficient maneuvers taken to avoid hazards and reach the waypoint. There was neither a main effect of data base integration ($F(1,16)=1.18(NS)$) nor of dimension ($F(1,16)=2.02(NS)$). However, the significant interaction between database integration and dimension ($F(1,16)=7.24(p<.05)$) suggests that trial completion times for the 3D integrated display were particularly slower than for the other displays (see Figure 9).

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4.2 Hazard Conflicts

Three types of conflicts were measured in any given trial: those predicted to occur with the traffic within the next 45 seconds (predicted traffic conflicts), actual traffic conflicts, and conflicts with weather. Arc sin transformations were used in the analyses of hazard conflicts to account for the use of proportions. For predicted traffic conflicts, a significant effect of dimension was found with $F(1,16)=47.57(p<.01)$ (see Figure 10). Trials in which the subjects used the 2D displays resulted in fewer predicted traffic conflicts and thus safety might be inferred to increase for these two displays. There was neither a significant main effect of data base integration $(F(1,16)=.02(NS))$ nor a significant interaction $(F(1,16)=.20(NS))$.

Similar results were found for actual traffic conflicts, although the percentage of conflicts was lower than for predicted conflict trials. Fewer actual traffic conflict trials than predicted conflicts were expected because ownship had to pass closer to the traffic for actual conflicts to occur. The 2D advantage was evident again through a significant effect of dimension $(F(1,16)=35.74(p<.01)$; see Figure 11). A significant main effect for data base integration was not found $(F(1,16)=.01(NS))$. However, a marginally significant interaction, $F(1,16)=3.97(p<.07)$, indicates that the cost of dimensionality was greatest when the data bases were integrated than when they were separated.

There was also a significant effect of dimension for weather conflicts, $F(1,16)=5.42(p<.05)$, again favoring the 2D displays (see Figure 12). In addition, the 2D integrated display, as compared to the other three displays, was particularly effective in supporting separation from weather hazards $(F(3,48)=3.53(p<.05))$. There was neither a significant effect of data base integration $(F(1,16)=2.30(NS))$ nor a significant interaction $(F(1,16)=1.24(NS))$.

4.3 Traffic Conflicts and Vertical Traffic Behavior

Traffic conflicts were also found to be affected by the joint influence of vertical traffic behavior and display type. For predicted traffic conflicts (see Figure 13) there was a significant effect of dimension for level, ascending, and descending traffic $(F(1,16)=4.86(p<.05)$, $F(1,16)=49.31(p<.01)$, and $F(1,16)=30.06$ $(p<.01)$, respectively). As figure 13 shows, the effect of dimension (solid vs. dashed lines) was stronger for the ascending and descending traffic trials, than for the easier level traffic trials. This suggests that the 2D advantage is more pronounced in non-level traffic trials due to ambiguity in judging the altitudes and vertical behavior of the other aircraft relative to ownship in the 3D displays.

Similar results were found for actual traffic conflicts, with the differences between level and non-level trials even more evident (see Figure 14). There was not a significant effect of dimensionality for level traffic trials $(F(1,16)=1.04(NS))$, but there was a significant advantage for the 2D displays for ascending and descending traffic trials with $F(1,16)=18.33(p<.01)$ and $F(1,16)=47.07(p<.01)$, respectively.

4.4 Subject Preferences

Upon completion of their experimental trials, the subjects were asked to rate the displays according to their preferences. A score of one corresponded to the most preferred display, with a score of four for the least preferred display. Results are similar to those found for conflicts previously discussed (see Figure 15). The means for the 2D displays were significantly lower than those for the 3D displays $(X^2(1)=31.344(p<.01))$. Thus the 2D displays were preferred by subjects over the 3D displays, with the 2D integrated display being the most preferred display overall. Subjective ratings did not reveal any effect of data base integration.

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4.5 Flight Path Deviations

In addition to trial completion time, previously discussed, flight path deviations (away from the straight line between ownship's initial position to the waypoint) were analyzed to assess maneuver efficiency. Figure 16 shows the Root Mean Square Error (RMSE) along the x-axis, representing horizontal maneuvers. A significant effect of data base integration was found $(F(1,16)=38.56(p<.01))$, with the separated displays resulting in the smallest deviations along the lateral x-axis and thus, the most efficient maneuvers. The effect of dimension was marginally significant with $F(1,16)=4.44(p<.06)$, reflecting the 2D advantage as was found with the hazard conflict and preference data. Data base integration and dimension did not interact $(F(1,16)=1.28(NS))$.

Vertical flight path deviations (along the y-axis) were also analyzed (see Figure 17). As with the x-axis deviations, a significant effect of data base integration was found $(F(1,16)=19.66(p<.01))$, however this effect was reversed. That is, the integrated displays resulted in the smallest deviations along the y-axis. The main effect of dimension and the interaction were not significant $(F(1,16)=1.29(NS)$ and $F(1,16)=.67(NS)$, respectively). Thus, the integrated displays led to smaller vertical deviations but larger lateral deviations. One possible explanation is that integrated displays led to a greater likelihood of choosing the lateral axis for maneuvering (i.e., display type effects maneuver strategy). The effects of display type on maneuver strategies are examined below.

4.6 Maneuver Strategies

It should be noted that the interpretation of changes in RMSE (or lack of changes) is somewhat ambiguous. This is because a change can result either because there is a symmetrical change in the magnitude of deviations, above and below the mean, or because there is an asymmetrical change, or

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bias toward positive or negative deviations. Furthermore, RMSE can remain constant, even if there is a substantial shift in deviations that produces a skew with many small deviations to one side, and a smaller number of large deviations to the other. In order to understand in more detail the quality of maneuvers, or the strategies employed, we examined in finer detail, the distribution of altitude and heading corrections on each maneuver, flown with the different displays. Figure 18 presents these data for the four displays, arrayed in the same format as in Figure 1. The axes within each figure show levels of no correction in either vertical maneuvering (horizontal axis) or lateral maneuvering (vertical axis).

The most pronounced interpretation that can be made from these data is the tendency for maneuvers with the two 3D displays on the right to avoid lateral correction (i.e., to be more "lined up" along the vertical axis). In contrast, maneuvers with the 2D displays (the two left panels), tend to show both a greater prevalence of lateral corrections, and of combined maneuvers, involving both lateral and vertical correction (i.e., points on the off axes quadrants).

One way of synthesizing the data shown in Figure 18 is to examine the signed mean position, along the x and y axis, as a function of the different display types. While the mean x (lateral) position was unaffected, the mean y (vertical) position was found to show a pronounced effect of display dimensionality, and one that differs as a function of whether the traffic was level or non-level (i.e., climbing and descending). Figure 19 reveals that level traffic fostered a tendency to descend, and that the 2D display fostered a tendency to climb.

In order to examine these tendencies further, we provide the distributions of points across the vertical and lateral axes in Figure 20. Within each of the top two panels is depicted the distribution of vertical position, observed when the intruder was in level flight (solid line), or was climbing or descending (dashed line). Within each panel, the data are collapsed over the two levels of data base integration. The panel on the left portrays data for the 2D displays. That on the right shows the data for

the 3D displays. The two panels at the bottom show the analogous representation for the lateral position.

Considering the vertical maneuvering in the top panels of Figure 20 first, we note that there does not appear to be an overall difference in maneuvering pattern between the 2D and 3D displays; but within each display type, the choice of vertical maneuvers was influenced differently by the vertical behavior of the intruder. For the 2D displays, when the intruder was level (solid line), there was a marked tendency to use vertical maneuvers (see upper 2D panel) and to avoid lateral maneuvers to some extent (see lower 2D panel). However, when the traffic ascended or descended (dashed line), there was a general bias to climb (see upper 2D panel), which existed independent of whether the intruder itself was climbing or descending. Again, lateral maneuvers tended to be avoided, as revealed by the peak at the zero lateral deviation point in the lower 2D panel.

For the 3D displays (right panels), lateral maneuvers were also limited (see lower 3D panel). Regarding vertical maneuvers with 3D displays (upper panel), level traffic yielded a pronounced tendency to descend, and to avoid most other vertical maneuvers (see upper 3D panel). However, when the intruder was climbing or descending with the 3D display, there was a greater tendency to descend or climb. The descent/climb change was dictated, in part, by the vertical behavior of the intruder (see Figure 21). If the intruder was climbing, there was a tendency also to climb, and if the intruder was descending, there was a tendency also to descend, a pattern observed by Merwin and Wickens (1996).

In addition to being affected by display type and vertical behavior of the other aircraft, maneuver strategies also depended on the initial lateral location of traffic hazards relative to ownship. We examined this by calculating the mean lateral position to the left (-) or right (+) of the flight path, as a function of different aspects of the conflict geometry. For example, for trials in

which the traffic was to the left of ownship, the subjects tended to maneuver to the left (see Figure 22). If on the other hand, the traffic initially was to the right of ownship, a maneuver to the right tended to be executed ($F(1,16)=9.16(p<.01)$). Thus, the subjects tended to fly toward the traffic's initial location so as to fly behind it as the traffic flew to the opposite side of the screen.

4.7 Effects of Data Base Integration

Analyses of the differences between trials in which one hazard biased the pilot to maneuver toward versus away from the other hazard, discussed previously, tend to reveal significant effects of data base integration, supporting the hypothesis that data base integrated displays would be most beneficial when pilots must consider both traffic and weather when deciding upon a maneuver. As shown in Figure 23, the integrated displays (solid line) resulted in significantly fewer trials with predicted traffic conflicts than the separated displays (dashed line) for weather hazard (bias toward traffic) trials (left most points; $F(1,16)=5.65(p<.05)$). A significant main effect of dimension was also found for both types of traffic hazard trials (bias toward weather and bias away from weather), once again revealing the 2D advantage ($F(1,16)=28.70(p<.01)$ and $F(1,16)=26.49(p<.01)$, respectively).

Data base integration also had an effect on weather conflicts as shown in Figure 24. For trials in which there was an initial traffic hazard with bias toward weather (middle points), a marginally significant effect of data base integration revealed fewer weather conflicts for the integrated displays ($F(1,16)=4.44(p<.06)$). As expected, the third trial type, traffic hazard (bias away from weather), did not result in a significant advantage for data base integration because the pilots could focus primarily on the initial traffic hazard, for both predicted traffic conflicts (Figure 23) and weather conflicts (Figure 24). In other words, the subjects were not required to integrate both traffic and weather information, as in the weather hazard (bias toward traffic) and traffic

hazard (bias toward weather) trials. The 2D advantage was again revealed by the significant effect

of dimensionality for the weather hazard (bias toward traffic) trials $(F(1,16)=5.50(p<.05))$.

5. DISCUSSION

5.1 Dimensionality, Data Base Integration, and Maneuver Strategy

The current experiment set out to explore the effects of dimensionality and database integration on conflict avoidance and maneuver strategies. It was expected that the 2D coplanar displays would result in the smallest number of conflicts with traffic and weather hazards. It was also hypothesized that for trials in which both traffic and weather had to be considered when deciding upon a maneuver, fewer hazard conflicts would result when the data base integrated displays are viewed. Table 1 provides an overall summary of the main results. Dependent variables are depicted down the rows, with the four displays represented in the columns. Within each cell is an entry that indicates the degree of success (+) or failure (-) of each display, in supporting the dependent variable in question. A "0" indicates relative neutrality with regard to the other three displays.

	Separated		Integrated	
Dependent Variables	**2D (A)**	**3D (B)**	**2D (C)**	**3D (D)**
Trial Completion Time	0	0	0	-
Predicted Traffic Conflicts	+	-	+	-
Actual Traffic Conflicts	+	-	+	-
Weather Conflicts	0	-	+	-
Preference	0	-	+	-
Lateral Efficiency	+	+	-	-
Vertical Efficiency	-	-	+	+
Maneuver Tendency	combined	vertical	combined	vertical
---with non-level traffic	climb	climb/descend	climb	climb/descend
---with level traffic		descend		descend

Table 1. Summary of results by display type

Examination of the four columns suggests an overall pattern of data revealing that the 3D displays did not serve performance very well, hence generally confirming the previous results of Merwin and Wickens (1996) and paralleling results obtained with 3D (perspective) displays for Air Traffic Control (May, Campbell, & Wickens, 1996; Wickens, Miller, & Tham, 1996). In particular the

3D integrated display appears to have fared most poorly. In contrast, both 2D displays supported performance relatively well, and the 2D integrated display appears to be best across the collective measures.

The collective results appear to indicate the role of all three performance mechanisms, discussed in the introduction: scanning, cognitive integration, and clutter. In particular, comparing the two 2D displays (A and C), the modest cost to the more separated display (A), observed in weather conflicts (Figure 12) and preference ratings (Figure 15), appears to reflect the cost of scanning, and or the cost of integrating spatially separate data bases, containing spatially related data; i.e., a low proximity display for a high proximity task (Wickens and Carswell, 1995). This hypothesis was supported by the separate analysis of these costs for predicted traffic conflicts in bias-toward versus bias-away problems, in which trials requiring the pilot to consider both weather and traffic were best served by the integrated display format (see Figure 23). Trials requiring only consideration of traffic (bias away from weather) did not reveal an advantage for the integrated displays, as expected. The effects of data base integration, while significant or marginally significant for some of the dependent variables, were considerably less robust than those of dimensionality. For example, effects of data base integration were revealed for weather conflicts and predicted traffic conflicts, but not for actual conflicts. It is possible that the results regarding data base integration were not as robust as those found for display dimension due to the difficulty in predicting whether the pilots would be biased toward or away from the secondary hazard. It was especially difficult to predict bias toward or away from weather (secondary hazard) for trials in which traffic was the primary/initial hazard. Although subject matter experts were surveyed to estimate the most likely maneuver to be selected to avoid a traffic conflict, there were always many other options available to the pilots, some more successful for hazard

avoidance than others. Thus, the estimation of bias is likely to have introduced error into our measurements used for the evaluation of the effects of data base integration.

In contrast to the modest assistance that data base integration offered the 2D displays, it is important to note that the data base integration was not helpful for the 3D formats; as evidenced in Table 1, it appears that the most integrated format (D), suffered more overall costs than the separated 3D format (B). This difference implicates the negative role of clutter, in the fully integrated display. Such clutter appears to have hindered the time required for pilots to complete a trial (see Figure 9), in a manner that we might expect, given the effects of clutter on visual search time.

As we noted at the outset, the most pronounced effect revealed by the data appears to be the negative effect of 3D ambiguity (McGreevy & Ellis, 1986), a cost that was most evident in the traffic conflicts, and thereby directly replicating Merwin and Wickens (1996), and providing results corresponding to those observed in weather maneuvering by Boyer, Campbell, May, Merwin, and Wickens (1995), and ground based Air Traffic Control by May, Campbell, and Wickens (1996) and Wickens, Miller, and Tham (1996). The current data also replicate the findings of Merwin and Wickens (1996) and Wickens, Miller, and Tham (1996), in observing that the 3D costs are greatly amplified if the traffic is not level.

Our analyses also examined the joint effects of conflict geometry and display, in fostering different maneuver choices. Merwin and Wickens (1996) had previously found a general tendency to select vertical over horizontal maneuvers, and one that is amplified by the 2D coplanar display format. In the current study we increased the height of the protected zone, in an effort to encourage a greater degree of lateral maneuvers. The present results reveal that pilots still tend to make more vertical than lateral maneuvers, as revealed by the greater dispersion of points along the vertical axis in Figure 18, and the sharp peaks at the center of the lateral distributions shown in the bottom panels of Figure 20. In

explaining this "vertical bias" we can only speculate that pilots do so because it is simpler, requiring a lower order of flight control to execute, relative to lateral deviations.

In contrast to Merwin and Wickens (1996), we did not find that the 2D coplanar format encouraged more vertical maneuvering in general. Instead, the 2D displays encouraged more climbing vertical maneuvers (vs. descending), particularly when the traffic was non-level, whereas the 3D displays encouraged more descending maneuvers, particularly when the traffic was level (see Figure 19 and the top two panels of Figure 20). Merwin and Wickens (1996) suggested that the tendency to fly under the traffic with the 3D, 30° elevation angle display (as used in the current experiment) resulted from the overlapping of ownship on the intruder aircraft when the other aircraft was located along the longitudinal (depth) axis. An ascending maneuver could result in the other aircraft being obscured by ownship due to the perspective nature of the display. Descending maneuvers, on the other hand, allowed the pilots to keep the other aircraft visible throughout the entire maneuver. The descending bias may also reflect tendencies in the actual flying environment in which the pilot is able to maintain eye contact longer with the other aircraft while descending as opposed to flying over the other aircraft. The 2D displays, however, did not suffer from the effects of occlusion due to the perspective format during ascents, and benefited from the unambiguous representation of the vertical axis on the lower panel, allowing a greater variety of maneuver strategies to be selected. It is not clear as to why there is a tendency to ascend for both ascending and descending traffic with the 2D displays.

Display dimension was also found to effect the choice of combined versus strictly vertical maneuver strategies (see Figure 18). Pilots implemented more combined maneuvers (as opposed to primarily vertical maneuvers) with the 2D displays, again replicating the findings of Merwin and Wickens (1996). It is possible that the unambiguous manner in which vertical information was displayed in the 2D displays allowed the pilots to divide attention between both axes, resulting in more

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combined maneuvers. Upon completion of the experiment, many pilots reported difficulties in determining the vertical behavior of traffic with the 3D displays. The ambiguity regarding the vertical dimension may have resulted in pilots focusing attention on the vertical axis, with less processing of the lateral situation occurring. Thus, more strictly vertical maneuvers were executed with the 3D displays.

Data base integration also appears to have some influence on the efficiency of maneuvering in the lateral and vertical axes. Integrating weather and traffic into a single display panel, whether 2D or 3D, appears to increase deviations in the lateral axis, while decreasing those diversions in the vertical axis (see Figure 18). Given the compensatory nature of these changes, it is plausible that something about the data base integration appears to foster a preference for lateral over vertical maneuvering, although it is not clear what the rationale for this choice might be.

Yet another replication of Merwin and Wickens (1996) involves maneuver tendencies for the 3D displays. When traffic was ascending pilots tended to ascend, and when there was descending traffic they tended to descend (see Figure 21). One possible explanation for the tendency to mirror the vertical behavior of traffic was noted by Merwin and Wickens (1996). Because of the 3D ambiguity involved in estimating the slope of the traffic's predictor line for climbing or descending traffic (the flight trajectory), it is likely that pilots using the 3D displays focused on the initial position of the intruder aircraft, above or below ownship, rather than assessing the ascending or descending behavior of the other aircraft. Thus, if the traffic was initially above ownship and descending, the pilots tended to descend in attempt to get below the other aircraft, and vice versa when the traffic was initially below ownship and ascending.

5.2 Suggestions for Future Research

Although data base integration occurs in many applications, such as weather maps, road maps, and land use maps, empirical support suggesting when and how to integrate data bases is

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lacking. It is noteworthy that many commercial airlines have integrated the Traffic alert Collision Avoidance System (TCAS) with the horizontal situation indicator for lateral navigation. The present study suggests that the effects of data base integration tend to vary according to task type. Studies which involve different methods of integration across a variety of tasks would provide a basis for guidelines which could be applied to real-world applications, such as Free Flight cockpit displays, to more effectively portray related information.

More studies involving comparisons between 2D and 3D displays would also aid in the representation of complex information in aviation as well as many other arenas. For instance, perhaps the 2D advantage could be overcome with training. In the current study subjects were given approximately the same amount of time to practice with the 2D and 3D displays, however the pilots were more familiar with 2D displays which are most often used in the aviation community. This real world experience with 2D displays could have strengthened the effect of the performance advantage for the 2D displays in the experiment. It would also be beneficial to explore the use of different predictors to compensate for the ambiguities inherent in 3D displays. Performance could be assessed to determine the optimal predictors for use in 3D displays. Finally, studies which portray more of the complexities in the flying environment would increase fidelity. For instance, pilots could be allowed to alter their airspeed as they would when they are actually flying. Or, the pilots interactions with air traffic controllers could be monitored. The added complexity would help insure that the results could be transferred to the cockpit of a real aircraft.

5.3 Concluding Remarks

Both hypotheses, regarding dimensionality and data base integration, were supported. The 2D displays tended to result in the best performance across measures when compared to the 3D displays. Trials which required the integration of both weather and traffic were best served by the

displays in which traffic and weather were overlaid within the same panel. A review of the various dependent variables in the current effort suggests that the 2D integrated display was the most optimum display overall. It is important to note that the current project focused on the individual operator, but in the actual flying environment a group of individuals, both pilots and air traffic controllers, interact with display technology and one another. Under Free Flight conditions, what display will ATC use so that interventions can be made if necessary? When should ATC get involved in preventing loss of separation? Answers to these questions and many more are critical to support the development and implementation of Free Flight, answers that could be applied to domains outside the aviation realm.

Figure 1. Four display types for the current experiment
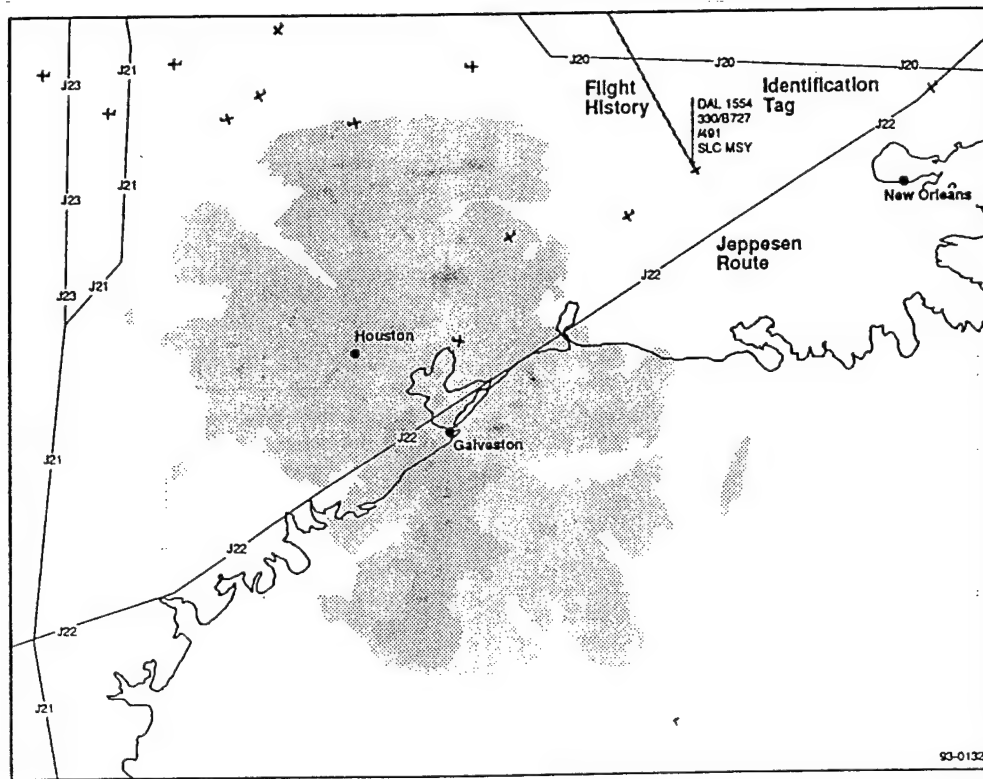
Figure 2. Weather, route, and aircraft location data overlaid on geographical map (reproduced from Heppner, 1993)
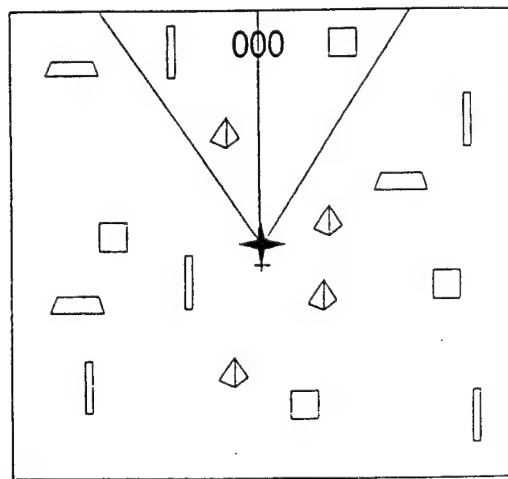
Figure 3. Wedge imposed on north-up map (reproduced from Aretz, 1991)
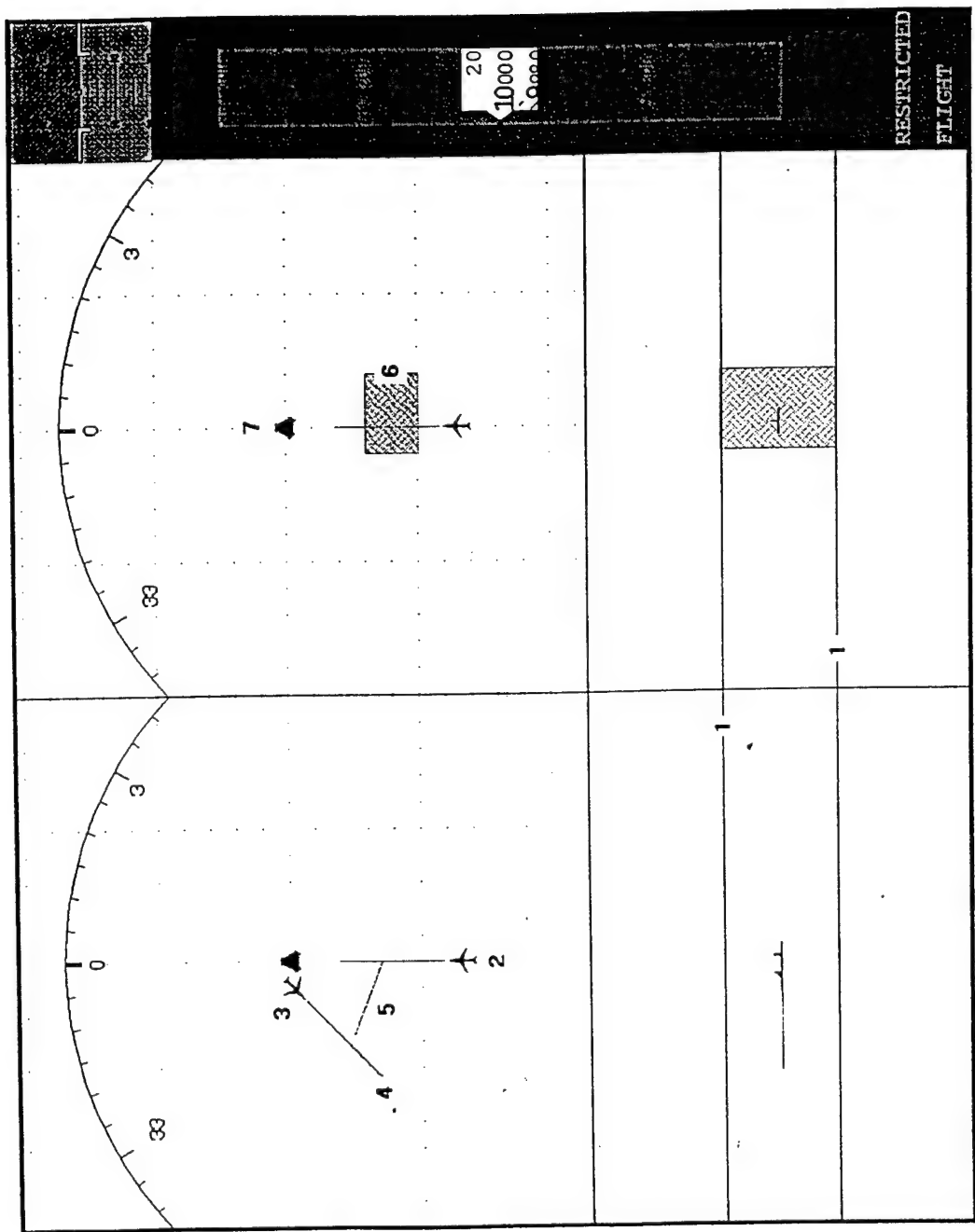
Figure 4. Display A (2D separated traffic and weather) with ownship and traffic flying straight and level and weather located in front of ownship
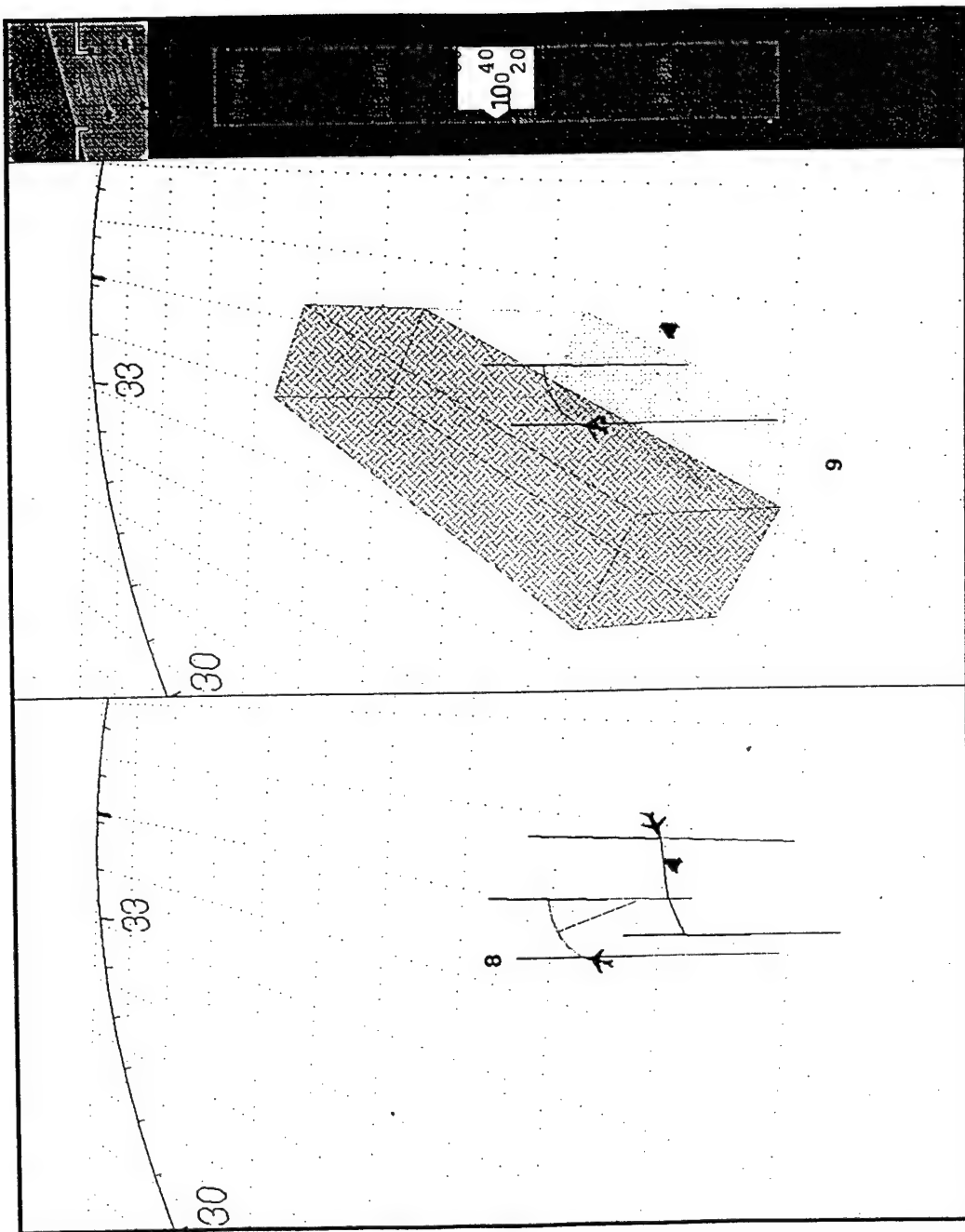
Figure 5. Display B (3D separated traffic and weather) with ownship turning right and descending while in a weather conflict; traffic currently a short distance below the vertical protected zone of ownship
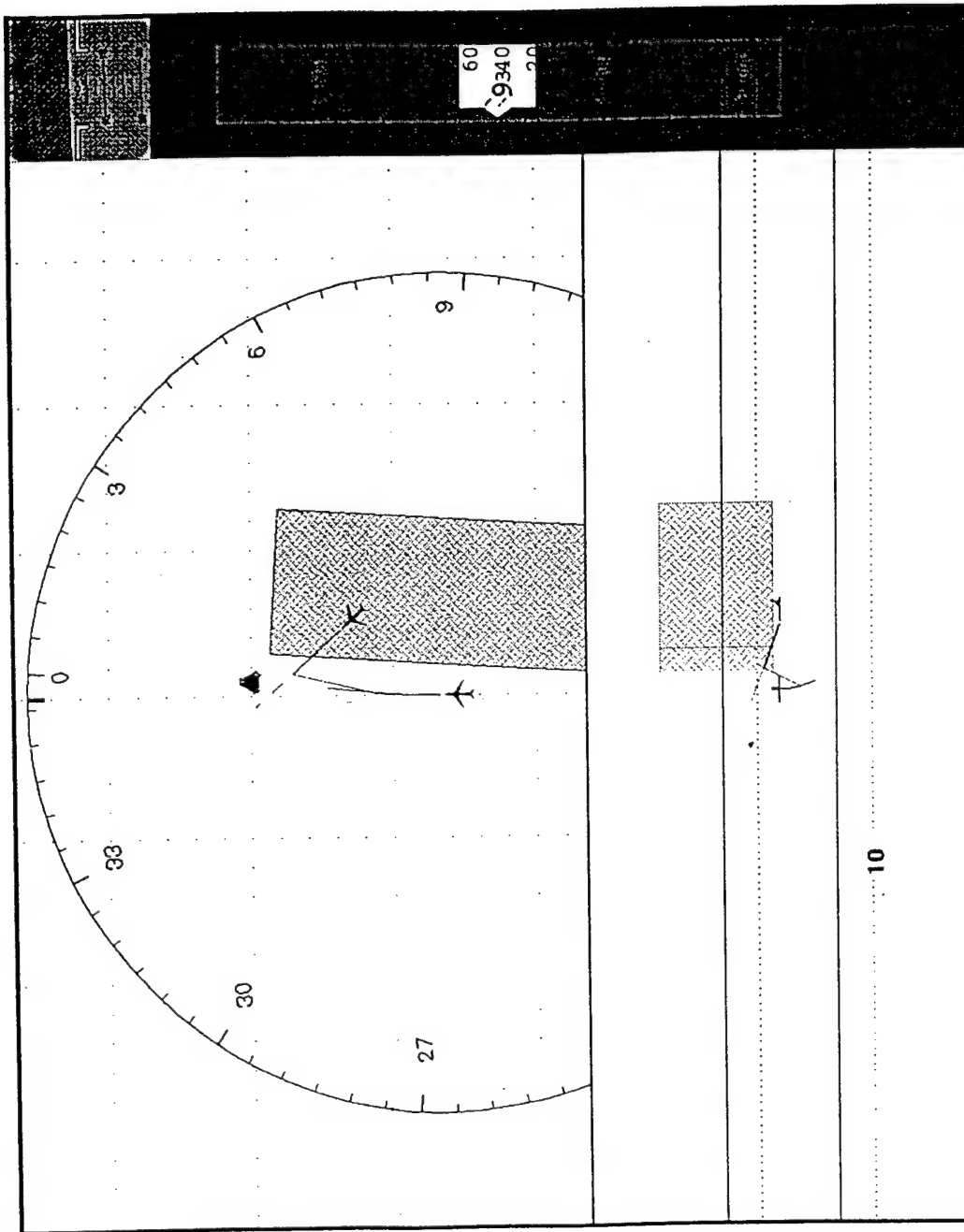
Figure 6. Display C (2D integrated traffic and weather) with ownship descending during a predicted conflict with the ascending traffic; weather located to the right and at an altitude above ownship

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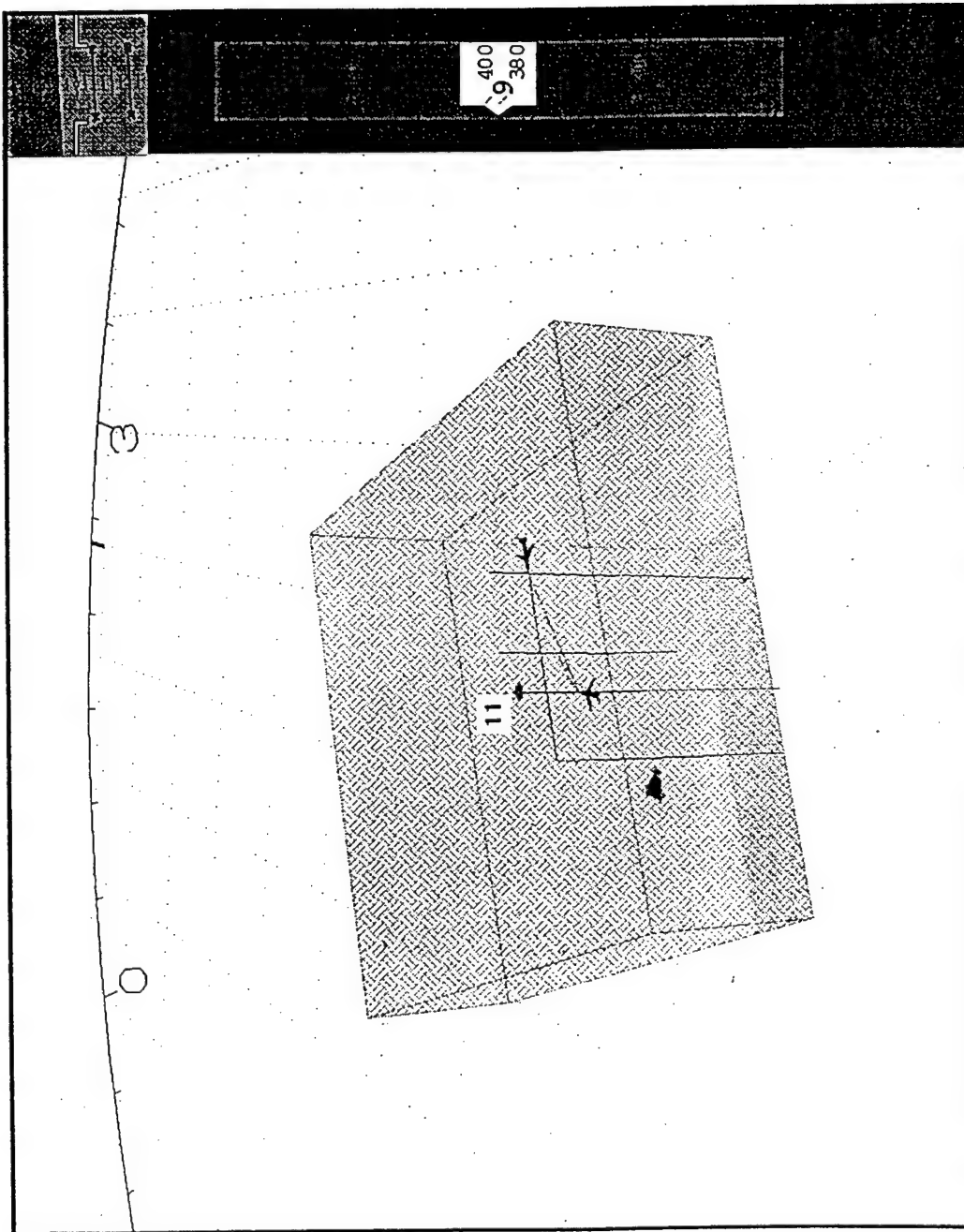
Figure 7. Display D (3D integrated traffic and weather) with ownship descending and turning right while in an actual conflict with the traffic; weather located above ownship
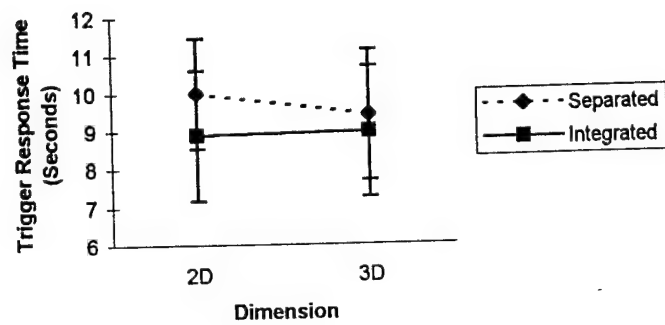
Figure 8. Trigger response time
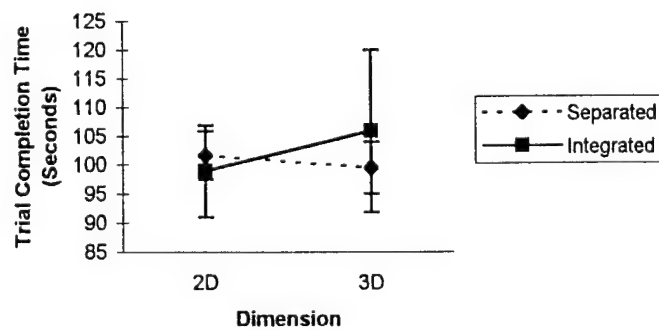
Figure 9. Significant interaction for trial completion time
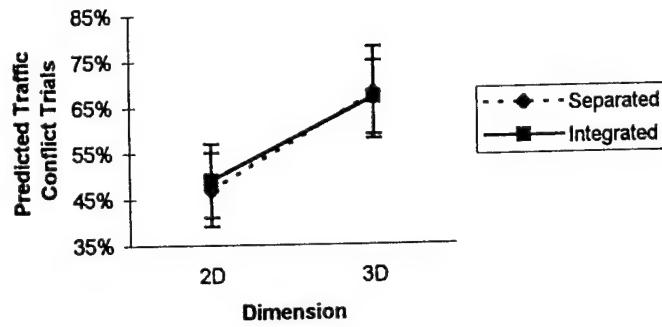
Figure 10. Significant 2D advantage for predicted traffic conflicts
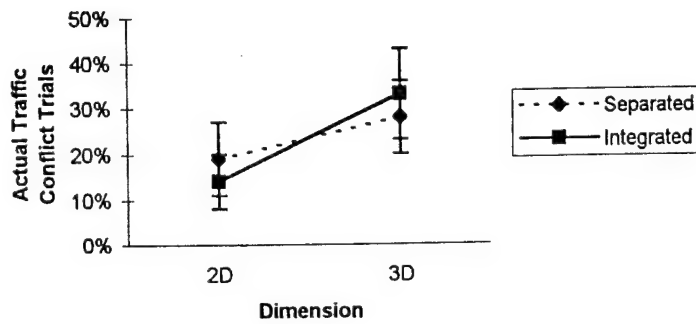
Figure 11. Significant 2D advantage for actual traffic conflicts
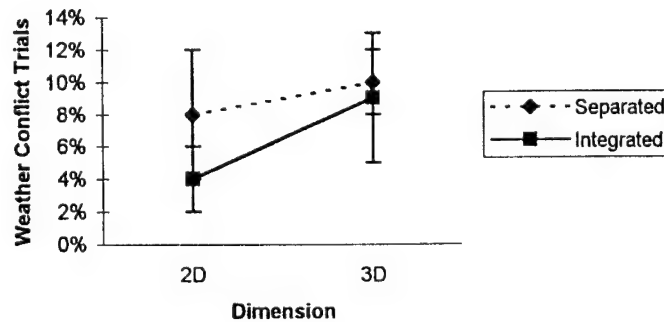
Figure 12. Significant 2D advantage for weather conflicts; significantly fewer weather conflicts for

2D integrated display
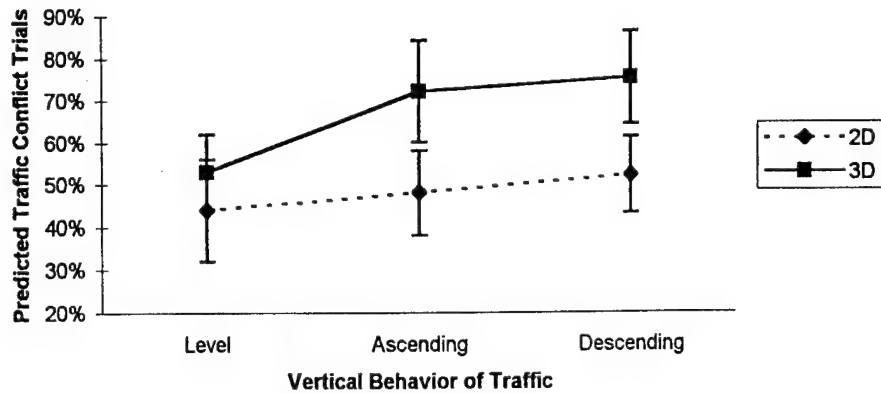
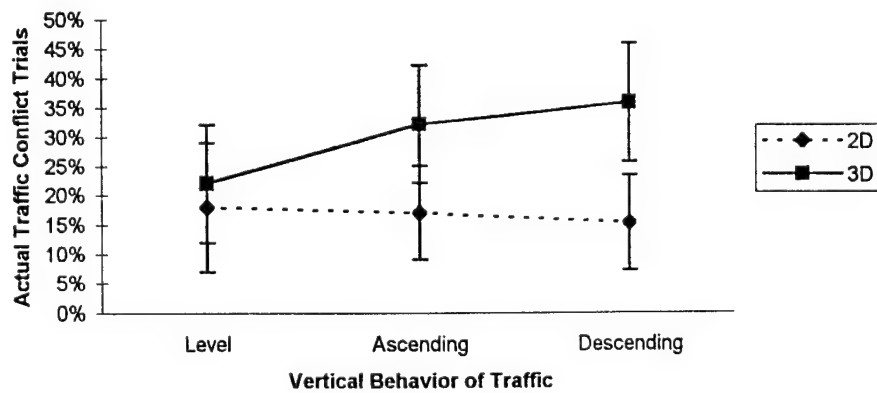Figure 13. Predicted traffic conflicts and vertical traffic revealing significant 2D advantage (stronger for non-level traffic than for level traffic)

Figure 14. Actual traffic conflicts and vertical traffic behavior revealing significant 2D advantage for non-level traffic
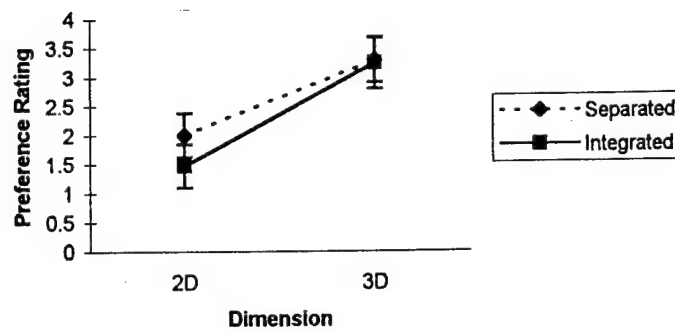
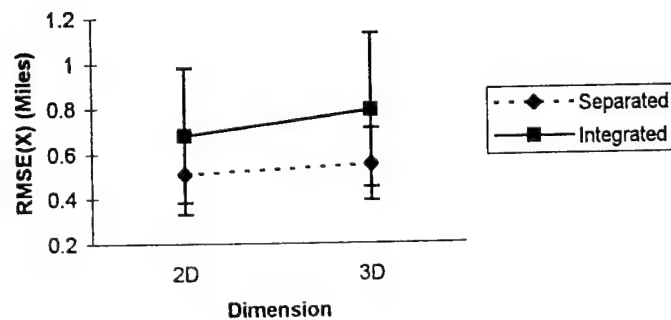Figure 15. Display preferences revealing 2D advantage

Figure 16. Significant effect of data base integration (favoring separated displays) and marginally significant effect of dimension (2D advantage) for horizontal flight path deviations
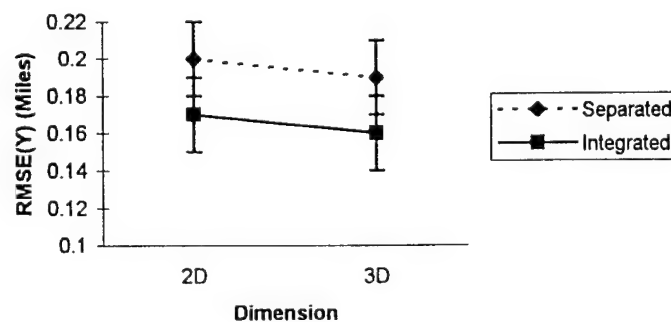

Figure 17. Significant effect of data base integration (favoring integrated displays) for vertical flight path deviations
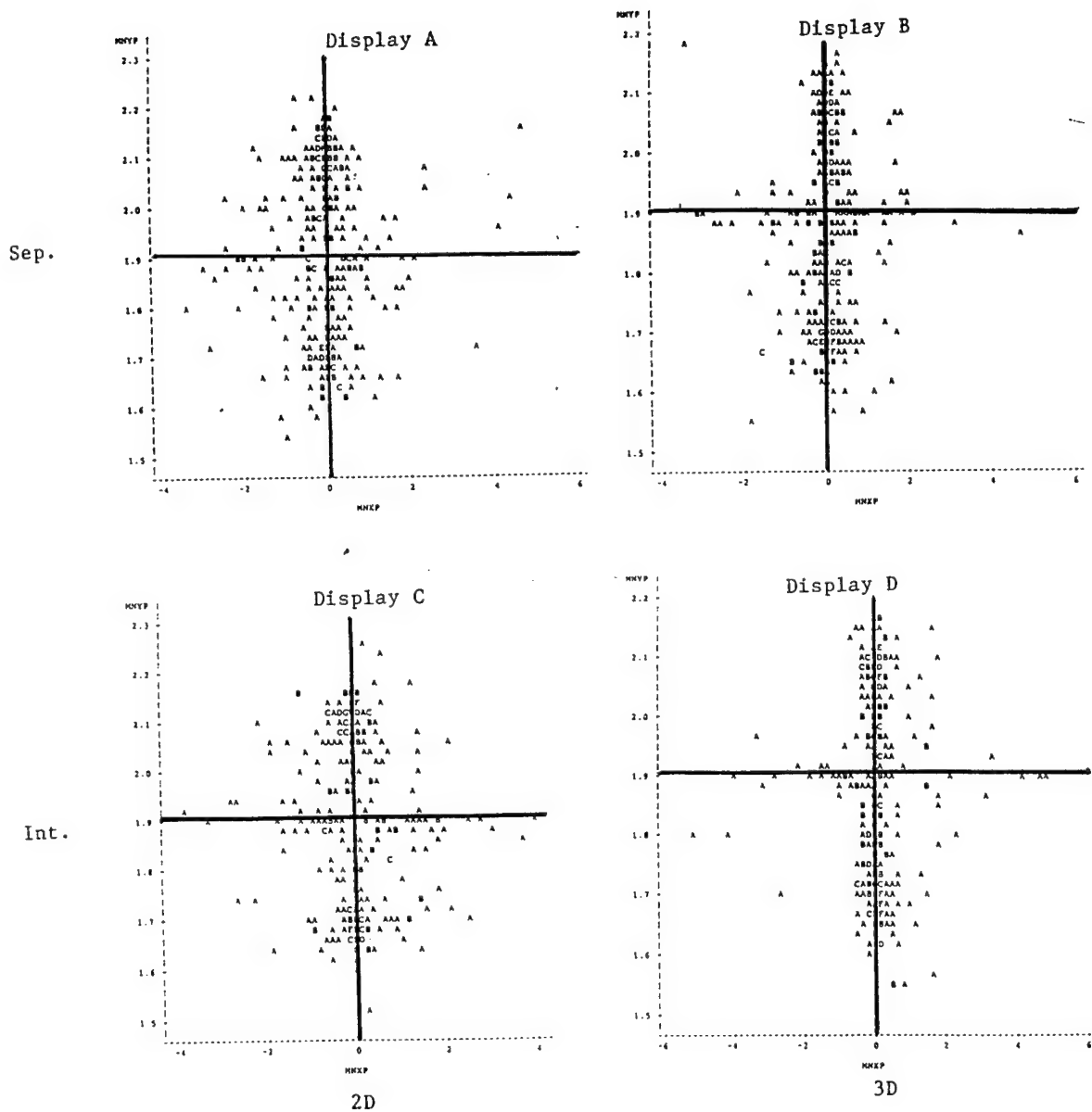
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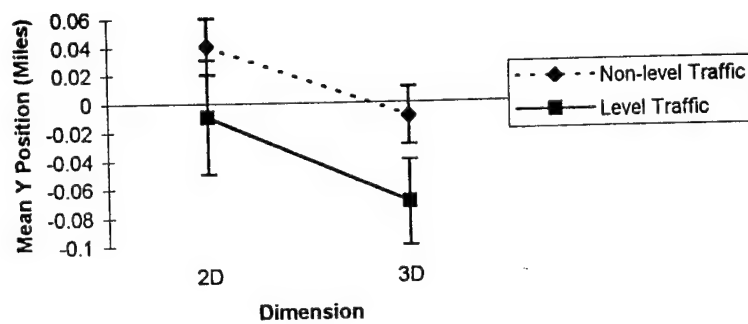Figure 18. Plots of mean x and y position (in miles) by display type

Figure 19. Vertical traffic behavior and mean y position for 2D and 3D displays
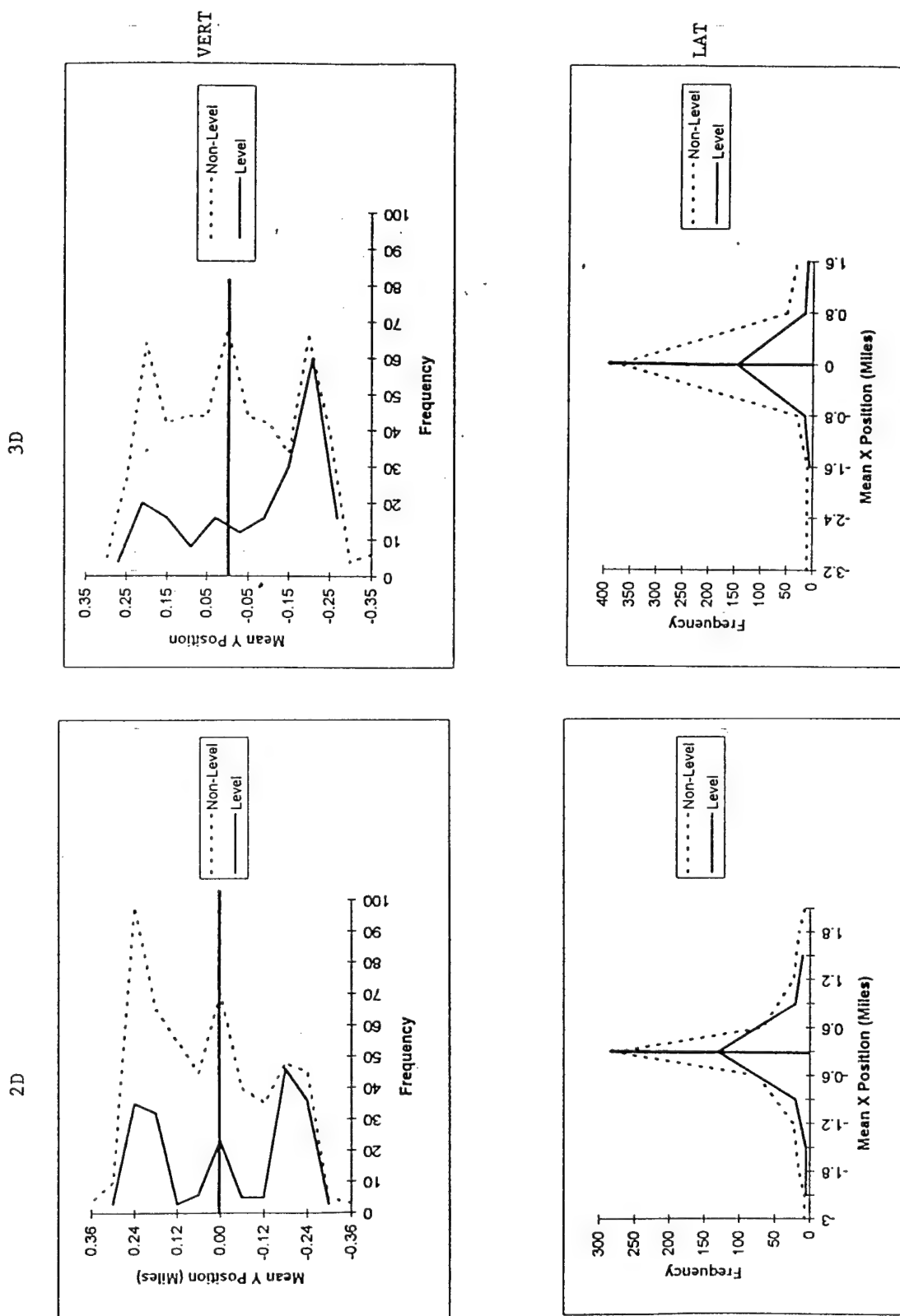
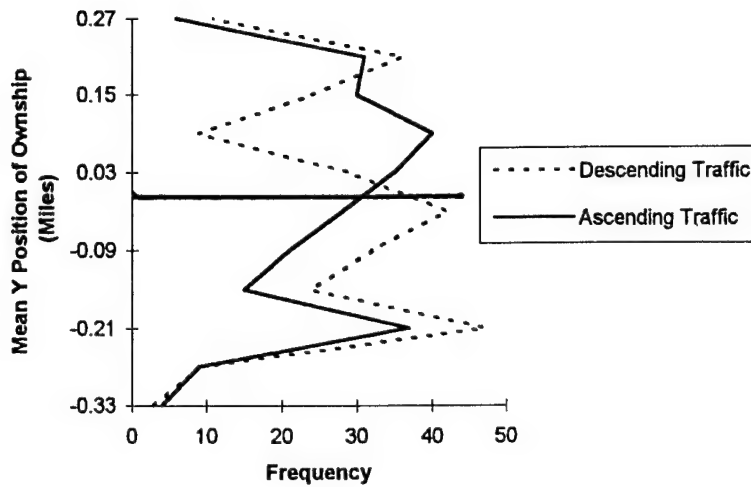Figure 20. Comparison of maneuver strategies across display types

Figure 21. Vertical traffic behavior and mean y position revealing tendency to ascend with ascending traffic and descend with descending traffic
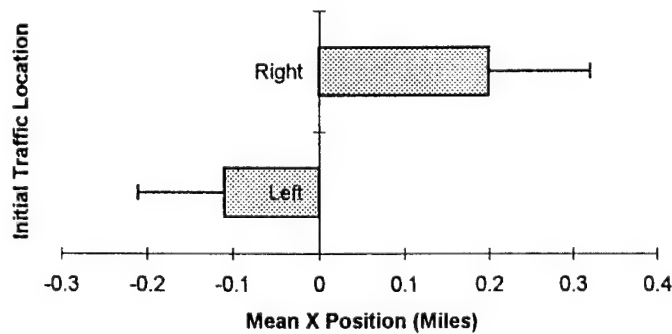
Figure 22. Horizontal traffic location and mean x position revealing the tendency to fly in the direction of the traffic's initial horizontal location
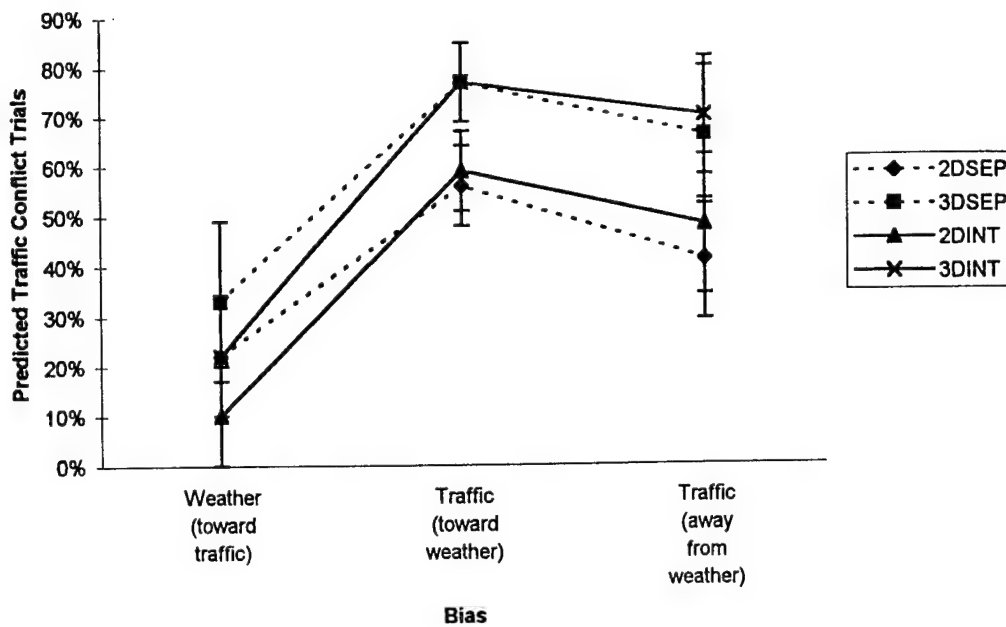
Figure 23. Effect of maneuver bias on percentage of predicted traffic conflicts revealing significant effect of data base integration for weather hazard trials
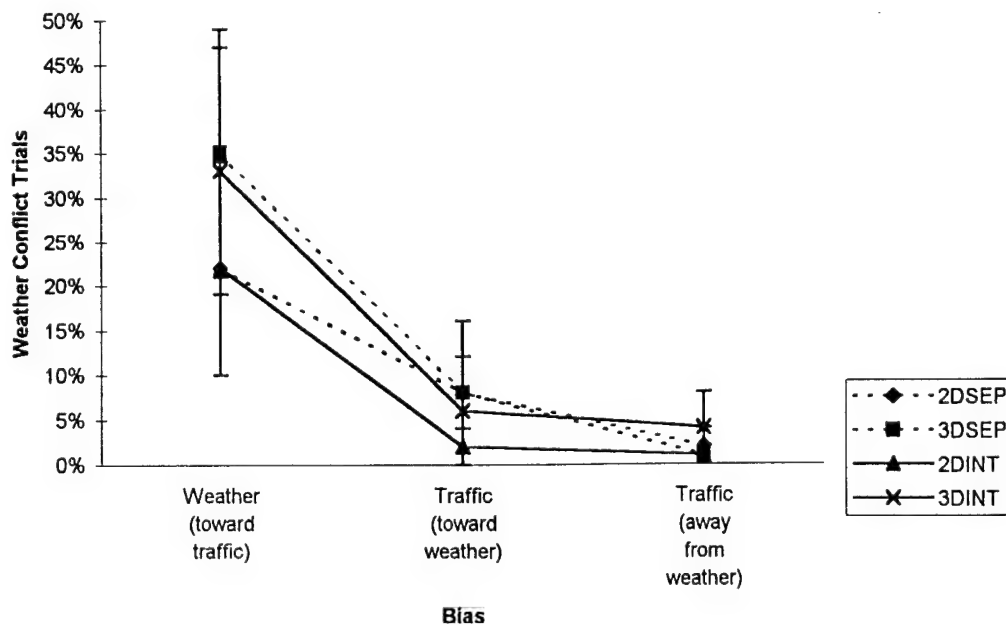
Figure 24. Effect of maneuver bias on percentage of weather conflicts revealing a marginally significant effect of data base integration for traffic hazard (bias toward weather trials)

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APPENDIX

Cockpit Displays of Traffic and Weather Information
Instructions to Participants

Introduction

The FAA and NASA have recently undertaken a research effort to examine specific ways to improve the efficiency of the National Airspace System. This program has been referred to as *Free Flight*, and involves providing airspace users with increased flexibility in selecting routes to their destinations. New systems are currently being developed to provide safe separation of traffic and distance from weather hazards while supporting more flexible flight paths. *Free Flight* has in fact been described as a system in which VFR flexibility is provided under IFR protection. A potential result of *Free Flight* is that ATC will have less control over traffic in the en route phase of flight than it does today. Because of this, pilots may be expected to take a greater role in monitoring their own separation from traffic and weather hazards; or more likely, monitoring the automated system that is providing separation. The present study examines two issues involved in presenting traffic and weather information in the cockpit. In particular we are interested in the following two questions. Should traffic and weather be integrated on a single display? And should traffic and weather be presented in co-planar (2-D) or perspective (3-D) formats?

Task Overview

In this study you will be asked to fly a series of short (1 to 2 minute) trials using a desktop IFR flight simulator which will present one of four experimental displays. The display provides information about the relative position, heading, and altitude of nearby aircraft and the relative position and altitude of no-fly zones/restricted airspace, depicting in this case a hazardous weather volume. In each trial there will be one other aircraft and one no-fly zone. You will be asked to fly a prescribed heading and altitude of 10,000 feet to a navigational waypoint while monitoring the display for potential conflicts with traffic and no-fly zones.

    - Traffic conflicts are defined as penetrations of the protected zone around your own aircraft (± 1500 feet, 3 mile radius.) No-fly zone conflicts occur whenever your aircraft flies into a red no-fly zone. Avoidance of traffic and no-fly zones are <u>equally</u> important. The primary goal of your task is to reach the waypoint as efficiently and rapidly as possible while maintaining safe separation from traffic and no-fly zones. The process of completing a trial is outlined below:

    - Fly the prescribed heading and altitude toward the navigational waypoint. The presence of the "Restricted Flight" text in the lower, right hand corner of the screen indicates that you will not be able to stray off course.

    - Monitor the display for anticipated traffic and no-fly zone conflicts. There will always be one other aircraft and one no-fly zone per trial, but only one of them will result in conflict if you do not maneuver from your current course. The other aircraft will always maintain its heading and vertical velocity, leveling off at a pre-determined altitude. In other words, the other aircraft will not react to your own aircraft's behavior.

- Assess the current and predicted situation, and as soon as you determine which maneuver to make to avoid the traffic or no-fly zone conflict, press the trigger on the joystick (this will turn the "Restricted Flight" text off so that you can maneuver freely) and maneuver around the conflict. Once you have avoided the conflict, return as soon as possible to a heading and altitude that will intersect the navigational waypoint on the display. Maneuvers should be as "efficient" as possible without compromising separation between your aircraft and other traffic and/or no-fly zones. That is, you should try to deviate as little as possible from your prescribed heading and altitude while safely maneuvering around the conflict. You may use any type of maneuver -- lateral, vertical, or a combination -- (other than change in airspeed, which is constant) that you feel is appropriate for the situation (i.e., there are no restrictions on the type of maneuvers you may select).

- The trial will end when you get within 3 miles of the waypoint and are at an altitude between 9,000 and 11,000 feet (successful trial completion), **or** when you pass the waypoint outside the specified parameters (unsuccessful trial completion).

4 Display Types, Symbology, and Conflicts

You have been provided with pictures of the four display types to familiarize you with the different displays, the symbology, and the types of conflicts you may encounter. The display type (A, B, C, D) is located in the upper, right corner of each picture. The numbers in these instructions correspond with the numbered labels on the pictures. Refer to the designated display picture as you read through the rest of these instructions. Please feel free to ask questions during this time.

Display A: 2D, separated traffic and no-fly zone display (4 panels). This is a 2-D display with traffic information represented in the left 2 panels and no-fly zone information in the right 2 panels. The top 2 panels consist of a top-down view, while the bottom 2 panels portray a forward view.

1. Ownship - Your aircraft is magenta and begins at an altitude of 10,000 feet.
2. Traffic/other aircraft - Other aircraft are gray under non-conflict conditions.
3. Predictor Lines - Extend from the nose of each aircraft (both ownship and other traffic) representing the predicted flight path 45 seconds (4 miles) into the future.
4. Threat Vector - Threat vectors are orange and point in the direction at which you will see the other aircraft pass closest to ownship. The threat vector moves closer to ownship's nose as time to conflict decreases. The end point of the threat vector moves closer to the traffic predictor line as your predicted separation decreases. Therefore avoid contact between the threat vector's endpoint and the traffic's predictor line at all times.
5. Grid - Dots are separated by one mile. One grid block is five miles by five miles. The grid is always 5000 feet below ownship's current position, although this feature is not visible in the 2-D displays.
6. Waypoint - The waypoint will always be at an altitude of 10,000 feet, directly in front of ownship at the beginning of each trial. Its horizontal position is depicted on the grid.
7. No-Fly Zone - No-fly zones are depicted as red rectangles. Notice that in this example the no-fly zone is positioned between ownship and the waypoint. This is known as a no-fly zone

conflict trial. If you continue to fly at the initial heading and altitude you will be in conflict with the no-fly zone but **not** the other aircraft. If the no-fly zone is initially to the left, right, above, or below ownship, on the other hand, a conflict will occur with the traffic but **not** the no-fly zone if the current altitude and heading are maintained.

8. Solid Yellow Lines - The solid yellow lines represent **current** vertical protected zone boundaries (1500 feet above and below ownship) while dashed yellow lines represent **predicted** protected zone boundaries. Note: dashed yellow lines are not present in this picture because ownship is maintaining a steady altitude. In this picture the other aircraft is flying level within the vertical protected zone, at the same altitude as ownship.

9. Restricted Flight Text - The red "Restricted Flight" text will appear at the bottom right corner of the screen at the beginning of each trial. Ownship will continue to fly toward the waypoint at an altitude of 10,000 feet until you decide which maneuver to make to avoid any traffic or no-fly zone hazards and press the trigger. The text will disappear once you press the trigger. It is important that you assess the current **and** predicted situation before pressing the trigger to maneuver.

Display B: 3D, separated traffic and no-fly zone display (2 panels - left and right). Traffic information is still presented on the left side of the screen with no-fly zones depicted on the right, as in the previous picture, but in a 3-D (rather than 2-D) format. All features of this display are equivalent to those of Display A (other than the solid and dashed yellow lines), in addition to the following:

10. Green and Yellow Vertical Posts: Green posts extend from both ends of predictor lines to the grid. The current and predicted horizontal position of ownship and other traffic can be determined by looking at the point at which the posts intersect the grid. The yellow zones on the posts represent the vertical protected zone, 1500 feet above and below ownship. The yellow zones on the posts can be used to determine if the traffic is within the vertical boundaries of the protected zone. For instance, by comparing the current and predicted posts on the other aircraft in the picture, you can see that the traffic is currently below the yellow zone, but if you maintain your current flight path, the other aircraft will be in the middle of the protected zone within 45 seconds. By comparing the lengths of ownship's posts to the other aircraft's you can also obtain relative height information between the aircraft.

11. No-Fly Zone Shadow: A blue "shadow" is projected onto the grid, representing the horizontal position of the no-fly zone. If the end points of ownship's green vertical posts intersect the grid within the "shadow" (as in the picture) you are either above, below, or in the no-fly zone.

12. No-Fly Zone Conflict: If you fly into a no-fly zone the wings of ownship will turn red, and the center portion of your aircraft will flash yellow and red, as in the picture. This feature is consistent across all four displays.

Display C: 2D, integrated traffic and no-fly zone display (2 panels - top and bottom). Unlike in the first 2 pictures you saw, in this 2-D display the traffic and no-fly zone information are integrated or overlaid within the same panels. As with the other 2-D display, the top panel is a top-down view, while the bottom panel represents a forward-view.

13. Predicted Traffic Conflict: When a traffic conflict is predicted within the next 45 seconds, the other aircraft and its predictor line (from the end of the threat vector to the nose of

the aircraft) turn white, and the threat vector extending from ownship's predictor line touches the predictor line of the other aircraft. This feature is also consistent across all the displays.

14: Dashed Yellow Lines: The dashed yellow lines represent the top and bottom of ownship's protected zone 45 seconds into the future. As you can see, the other aircraft is currently within the vertical boundaries of the protected zone because it is within the **solid** yellow lines. However, the end of the traffic's predictor line is outside the **dashed** yellow lines, indicating that if you continue along your flight path, the other aircraft will be above your protected zone within 45 seconds and you will no longer be in a conflict situation.

Display D: 3D, integrated traffic and no-fly zone display (1 panel). This 3-D display integrates the traffic and no-fly zone information in a single panel.

15. Current Traffic Conflict: When the other aircraft is currently within ownship's protected zone, the other aircraft turns yellow and the threat vector reaches the nose of ownship.

16. No-Fly Zone Markers: If ownship is within 1500 feet of the bottom of the no-fly-zone, a purple mark will appear on ownship's vertical post within the yellow zone. The marker's position corresponds with the altitude of the bottom of the no-fly zone. A red marker will appear if ownship is within 1500 feet from the top of the no-fly zone, and represents the altitude of the top of the no-fly zone. These markers will also be present in Display B, although it is hard to see in the corresponding picture. Note: only a purple marker appears in the picture for Display D.

If you do not have any further questions we will proceed with the schedule below.

<u>Schedule</u>
- Day 1:
  - 8 Introductory trials (2 per display type)
  - 2 Practice trials with Display A
  - 21 Trials with Display A
  - Short Break
  - 2 Practice trials with Display B
  - 21 Trials with Display B
- Day 2:
  - 2 Practice trials with Display C
  - 21 Trials with Display C
  - Short Break
  - 2 Practice trials with Display D
  - 21 Trials with Display D
  - Post-Experiment Questionnaire